CHAPTER 1: INTRODUCTION

1.1 Problem Statement

UTP has been involved in ROBOCON robot competition for several years. However there is lack in research and systematic development of robot mechanism, the robots produced was unable to complete the task of competition. One part of the problems is on gripping part. For example, the gripper could not grip and lift the workpiece required in the competition.

1.2 Problem Identification

Review was made from previous designs of UTP ROBOCON grippers. The findings can be described as below:

i. Gripper need to provide enough gripping force. This can be proved crucial as the gripper didn’t provide sufficient force to grip the specified workpiece.
ii. Gripper was not attached with any sensor to guide robot to detect the presence of workpiece and subsequently detect the displacement length of mechanisms in robot. As a result, the robot had been unable to perform the tasks within 2 minutes of competition time.
iii. Workpiece that is lifted loosen over time and eventually fall during lifting. The gripper had been able to grip workpiece when robot at static condition but not when lifting whereas there is dynamic condition.

In order to produce a gripper with the ability to complete the competition tasks, an innovative and systematic development of robot gripper is needed.

1.3 Project Objectives

i. To redesign, analyse and fabricate a prototype model of a robot gripper for lifting application.
ii. To verify analysis using simulation software on dynamic mechanism.

1.4 Scope of Work

Robot gripper prototype constructed will have the capability of performing the competition tasks and perform it repetitively. The tasks are:

i. Lift specified shape and size of workpieces and hold it in air until end of competition duration. Lifting displacement is 50cm vertically from ground.
ii. The gripper will grasp the workpiece and lifter will lift both gripper with the workpiece and bring it at least 50cm above ground.
iii. Its dimension must fit within specified starting area dimension which is 1m width X 1m length X 1m height.

Simulations to be developed meanwhile consist of two tasks:

i. Perform dynamic simulation on gripping mechanism to estimate time taken.
ii. Perform finite element analysis on load stress and deflection to identify feasibility of gripper structure design.

Some assumptions are considered in designing the gripper which:

i. Base of robot is negligible. Thus the prototype will consist of only gripper and lifter.
ii. Since there is no robot base and no movement of robot, the workpieces are feed into gripper jaw opening by external action.
iii. The prototype constructed will be autonomously operated using pre-built main circuit board.
iv. Cost for project research and prototype are neglected.

CHAPTER 2: LITERATURE REVIEW

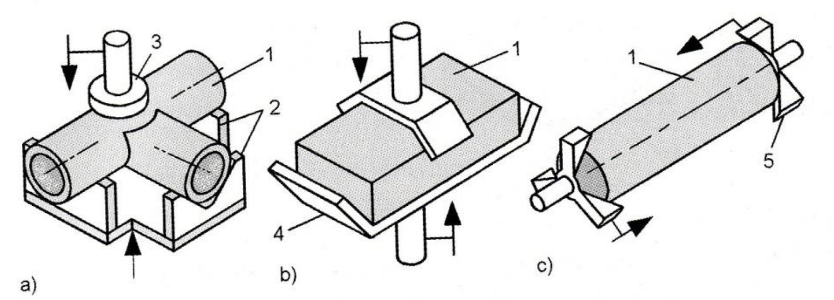
2.1 Active Pair Mating

The term “active pairs” is interacting components, eg; gripper jaw and workpiece. Table 1 below shows classification of gripping categories [1]:

Table 1: Classification of gripping categories [1]

Active Pair		
Gripping Method	**Non-penetrating**	**Penetrating**
Impactive (motion of solid jaws produce grasping force)	Clamping jaws, chucks collets	Pinchers, pinch mechanism
Ingressive (surface deformation or penetration to predefined depth)	Brush elements, hooks, hook and loop (Velcro)	Needles. pins, hackles
Contigutive (direct contact eg ; adhesion)	Chemical adhesion, surface tension forces	Thermal adhesion
Astrictive (binding forces between surfaces)	Electrostatic adhesion	Magnetic grippers, vacuum suction

For typical two points gripping, it is ideal to suppress all degrees of freedom. Figure 1 shows different active pairs with its corresponding degrees of freedom [1]:



a) Almost all degrees of freedom are suppressed

b) All degrees of freedom are suppressed

c) All but one degreed of freedom are suppressed

Figure 1: Active pairs with its corresponding degrees of freedom [1]

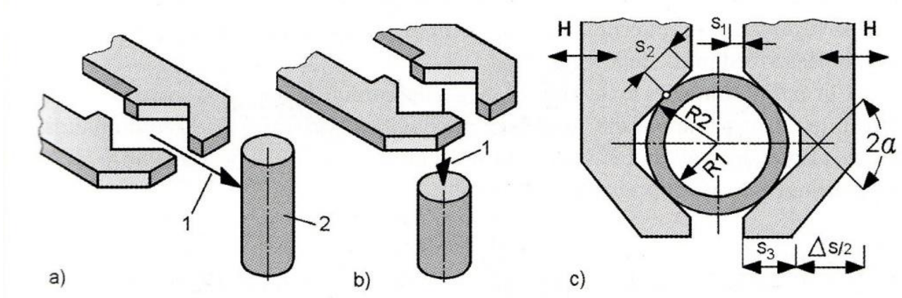
2.2 Gripping Procedure, Conditions and Force

Gripping procedure can be divided into 4 phases [1]:

i. Preparation for contact – Appropriate orientation of objects following predefined motional pattern.
ii. Prehension - Establishing contact between object and gripping surface. Workpiece subjected to static forces and moments.
iii. Retention – Manipulation of object in space. Dynamic forces and moments occur.
iv. Release of object.

How well a workpiece is secured during gripping depends on the number of degrees of freedom following prehension. An ideal grip is to surpress all (0) degree of freedom so that no part of object can move or rotate when gripper jaws are closed.

Design of gripper jaw also affects choice of gripper. It is important to decide whether axial or radial gripping is more appropriate, which to great extent depends on logical considerations. The following separation distances can be estimated for both axial and radial gripping. Figure 2 shows the illustration of these gripping [1]:



a) Radial gripping

b) Axial gripping

c) Gripper dimensions

Figure 2: Axial and radial gripping illustration [1]

For radial gripping, the opening width, H is given by [1]:

$$H = R_2 + S_1 + S_3 + \left(\frac{R_2}{tan\ \alpha} + S_2\right).\cos\alpha - \frac{R_1}{\sin\alpha} \qquad \text{Eq. 1}$$

S_1 = play in jaw travel during enclosure

S_2 = reliability tolerances for contact points on large workpiece

S_3 = play in jaw travel during opening (drive − in clearance)

R_1 = minimum radius size

R_2 = maximum radius size

For axial gripping, the opening width, H is given by [1]:

$$H = \frac{0.5.\Delta S + S_3 + R_2 - R_1}{\sin\alpha} + S_1 \qquad \text{Eq. 2}$$

Design of gripper is influenced significantly by forces to ensure reliable prehension of object. Some of factors that determine required gripping force:

i. Resultant force as vector sum of all acting forces.
ii. Object geometry and gripping points.
iii. Design of gripper jaws and shape mating.
iv. Material and surface of gripper jaws.

By using Newton’s law of interactions, it states that each action results in same amount of reaction. This means that it makes no difference whether only one jaw or more are applied. A 200N gripping force will result in 200N reaction force. Taking example of impactive grippers, the gripping force can be calculated by [1]:

$$F_G = \frac{m.g}{\mu.n} \qquad \text{Eq. 3}$$

Where:

g = acceleration due to gravity

n = number of fingers and jaws

μ = friction coefficient between gripper jaw and workpiece

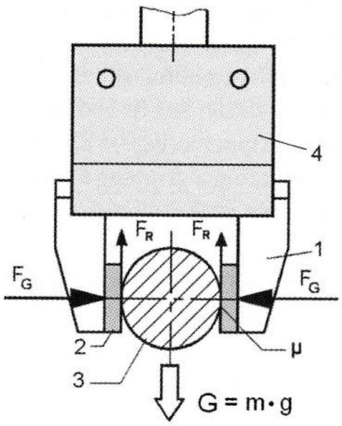
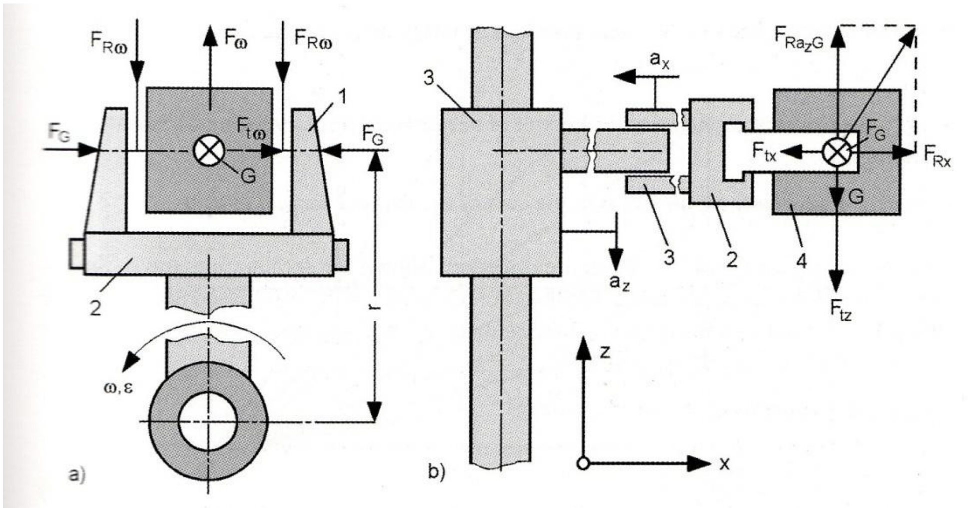


Figure 3: Forces acting at rest and during motion [1]

The choice of safety margins depends on the type of motion performed:

i. Safety factor of 2 for normal applications.
ii. Safety factor of 3 for motion in several axial with low acceleration and braking.
iii. Safety factor of 4 for large acceleration and sudden impacts.

In calculating forces reacting during gripping, these notations are used in figure 4 below in the calculation:



a) plan view b) side view

F_G = gripping force

F_R = frictional force

G = gravitational force on workpiece mass m

ε = angular acceleration

r = distance from pivot centre to workpiece

Figure 4: Forces reacting during gripping [1]

The required gripping force [1]:

$$F_G = \frac{m}{2.\mu}\sqrt{r^2.\omega^4 + g^2} + m.r.\varepsilon \qquad \text{Eq. 4}$$

2.3 Gripper Characteristics

A high quality gripper in general should possess the following properties [1]:

i. Optimum adjustments of gripper structure to operations performed.
ii. Options for different workpiece shape and size.
iii. Optimum gripping force.
iv. Low number of links and joints.
v. Small installation space and mass.
vi. Avoidance of damage to objects.

vii. High object positional accuracy.
viii. Simple control and short action times.

2.4 Gripper Jaws

Impactive gripper is one of the most common types of robotic gripper. There were 2 types of impactive gripper jaws which are:

i. Concentric Jaws Robot Gripper. The advantages of the gripper are as follows:
   a) Curvy shape which increase contact surface.
   b) Capable to grip wide range of cylindrical parts.
   c) Accurate gripping.

Figure 5: Concentric robot gripper [6]

ii. Parallel Jaws Robot Gripper. The gripper has following properties:
   a) Flat and parallel jaws allow gripping of any shape.
   b) Highly reliable.
   c) Large gripping range.
   d) Easy to use.

Figure 6: Parallel robot gripper [6]

2.4.1 Jaw Factor

The style of jaw is very important in determining the force required. Two types of jaws:

i. Friction grip.

   It relies totally on the force of the gripper to hold the part. The "squeeze" of the gripper does all the gripping work.

ii. Encompassing grip.

   It works by cradling the part. Encompassing jaws provide a major advantage of ratio 4 to 1 in terms of force required. This is because the jaws protect the part from dropping. Therefore the inefficiency of the slides helps to keep the part in place.

In comparison, encompassing style is preferred for strength and stability. Furthermore, friction grip requires four times the force to handle the same part as an encompassing grip.

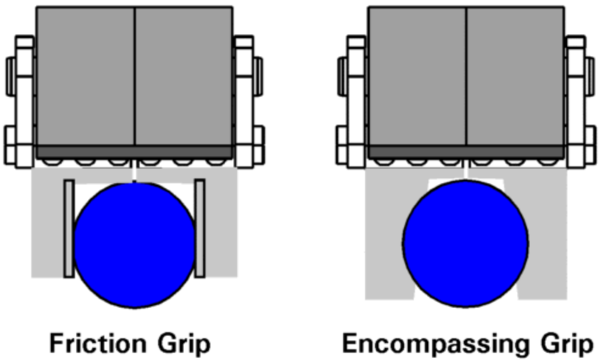


Figure 7: Friction grip and encompassing grip [5]

2.4.2 Part Weight

Weight determines the required gripping force which coming from both from gravity and from acceleration. Both properties must be considered when determining the gripper force required. Equation to estimate the gripping force can be described as below [5]:

Grip Force = (Part weight) x (Gravity + Acceleration) x (Jaw factor)

Eq. 8

2.4.3 Torque Requirements

There are two sources of torque which can be addressed separately. Both torques will then be summed up:

i. **Torque from the robotic gripper**

The longer the jaw, the greater the torque of the gripper imposes on itself. Figure below shows calculation of the gripper torque:

Gripper Torque = Grip Force x Jaw Length (measured from gripper face to the center of gravity of the part)

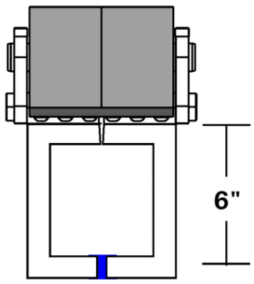


Figure 8: Gripper length measurement to the center of gravity of part [5]

ii. **Torque from the workpiece**

In the first case shown below, the acceleration is in horizontal direction. Thus the force from gravity need not be considered. However, in the second case, whereas the acceleration of the robot is vertically, extra gravity value needed to be added because gravity will also be trying to torque the jaws. Generally, workpiece torque can be described as:

$$(\text{Acceleration}) \times (\text{Part weight}) \times (\text{Jaw length}) \qquad \text{Eq. 9}$$

CHAPTER 3: METHODOLOGY

3.1 Research Methodology

Research regarding development of an improved gripper had been made through methods as below:

i. Literature review and reference from robot gripper books and mechanical design method.
ii. Held an interview with ROBOCON Research Department personnel to identify flaw from previous gripper design.

3.2 Project Activities

Throughout the project, activities will start from problem identification until completion of gripper prototype. Detail activities are listed as below:

i. Problem identification.
ii. Literature review.
iii. Design planning.
iv. Develop engineering specifications.
v. Develop design concept.
vi. Develop design.
vii. Evaluate design
viii. Manufacturing process.
ix. Fabrication of prototype.

The Gantt chart of project progress is shown in the appendix. The detail breakdown for the design is shown as in figure 9:

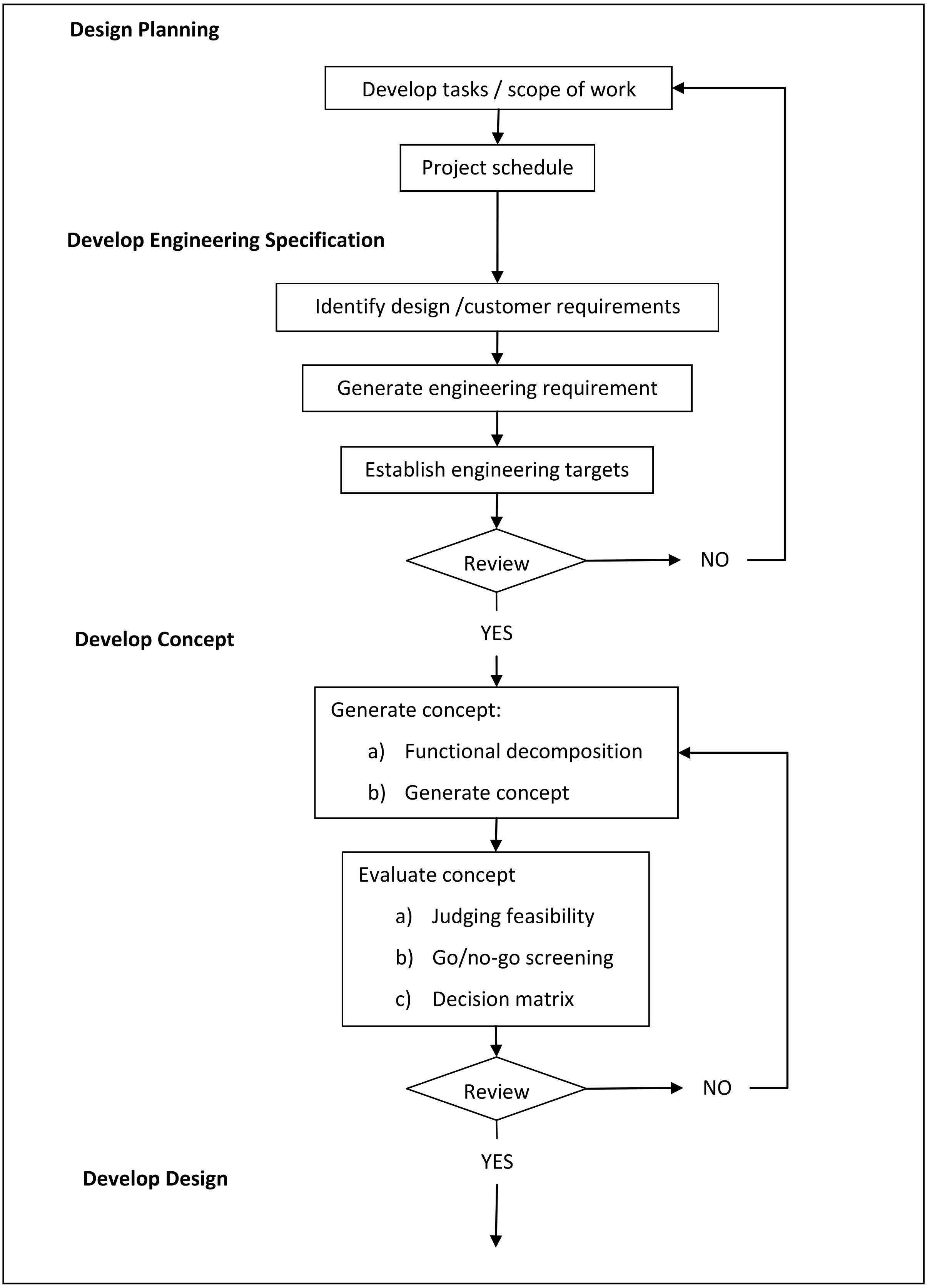


Figure 9: Project flowchart part I

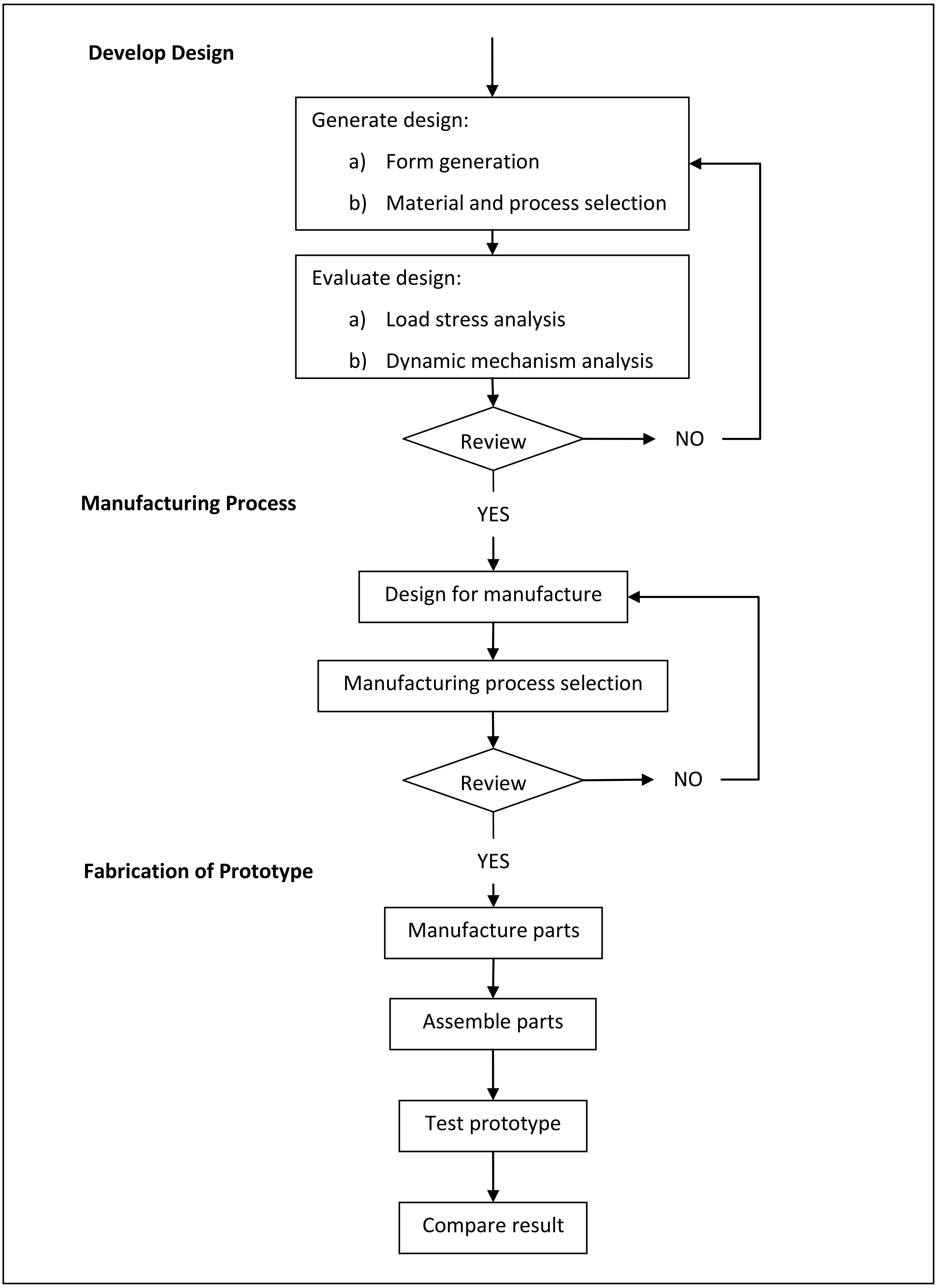


Figure 10: Project flowchart part II

3.3 Tools Required

Tools required will consist mostly of software and crafting tools for fabrication. Table 2 below shows tools required and its function:

Table 2: Tools required and its function

No	Tools	Function
1	AutoCAD software	Design and drawings of gripper
2	ADAMS software	Simulation of gripper mechanism

CHAPTER 4: PROJECT WORK, DISCUSSION AND RESULT

This chapter discuss on the whole progress of project methodology. This includes identifying required gripper specifications, conducting mechanical design process for robot gripper manipulator, evaluation of constructed gripper design using simulation software, manufacturing process and fabrication of prototype and finally testing of prototype to acquire final result.

4.1 Develop Engineering Specifications

The first stage is to develop the engineering specifications. These specifications consist of abstract words and value. Development of engineering specifications for robot grippers requires 4 steps until the completion of engineering specifications. These steps are:

4.1.1 Step 1: Identify Customers

Since this is a prototype product, there is no consumer. In this case, the organizer of ROBOCON competition and UTP ROBOCON team are considered as the customers. Organizer of ROBOCON competition also had issued regulation book on required robot specifications. This regulation is considered when developing the specifications.

4.1.2 Step 2: Customer Requirement

For the UTP ROBOCON team, requirements are:

i. Small gripper structure.
ii. Options for different workpieces shape.
iii. Sufficient gripping force.
iv. Low number of links and joints.
v. Low mass.
vi. Avoidance of damage to objects.
vii. Short action times.
viii. Material and manufacturing availability.

The organizer of ROBOCON competition stated the requirements as indicated in the competition rules book [9]:

4.1.2.1 Robot Manipulator Specifications

a) Robot gripper type is autonomously controlled.

b) Dimensions :
   i. Height not exceeding 1000mm.
   ii. Width not exceeding 1000mm.
   iii. Length not exceeding 1000mm.

c) Electrical connection of robot must be via wired cable. Wireless connection is not allowed.

d) Voltage for electric power supply not exceeding 24V.

e) Total weight for a robot must not exceed 10kg.

4.1.2.2 *Workpiece Description*

There are two types or shapes of objects to be gripped. Which are “butter” and “cheese”. The robot must be able to lift either one or both of the objects and hold it in the air. During contact with the objects, no shape deformation or punching fully or partially through the objects is allowed. The objects description is as follows:

i. **Cube** :
   Dimension: 300mm in cube shape
   Material: Low density polystyrene
   Weight: 350g
   Surface texture: Rough

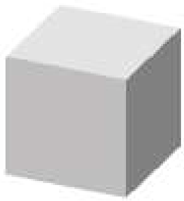


Figure 11: Cube [9]

ii. **Cylinder** :
   Dimension: 300mm in diameter and 200m in height
   Material: Low density polystyrene
   Weight: 300g
   Surface texture: Rough

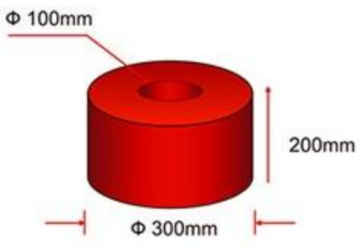


Figure 12: Cylinder [9]

4.1.3 Step 3: Determine Engineering Specifications

Engineering specifications are determined based on the restatement of design problems and requirements in terms of parameters. These specifications also have target values:

i. Gripping force (N)
ii. Gripping range per jaw (mm) or (˚)
iii. Gripped objects type (qty)
iv. Action times (s)
v. Overall dimensions (m)
vi. Deadweight (kg)

4.1.4 Step 4: Set Engineering Targets

These final steps used to set the target value for the engineering specifications made on previous step. Some of the target is already determined by organizer of the ROBOCON competition while some need to be determined:

i. Gripping force (N)

The weight of ‘cube’ and ‘cylinder’ are 350g and 300g respectively. The maximum load capacity is then:

$$\mathrm{m_{max}} \times \mathrm{g} \times \mathrm{FOS}(2) = 6.88\ \mathrm{N}$$

From equation 8, the minimum gripping force can be estimated:

$$\mathrm{m} \times (\mathrm{g} + \mathrm{a}) \times \text{jaw factor} \times \mathrm{FOS} = 27.5\ \mathrm{N}$$

ii. Gripping range per jaw (mm)

Taking width dimension limit minus clearance range, maximum range for jaw opening is:

$$H = 800\ mm$$

iii. Gripped objects type (qty)

There are 2 shapes of workpieces to be gripped, which are cube and cylinder.

iv. Action times (s)

Maximum time taken is 10s for both gripping and lifting.

v. Overall dimensions (m)

Not exceed 1m length X 1m width X 1m height.

vi. Deadweight (kg)

Total weight shall not exceed 10kg.

4.1.5 Engineering Specifications Results and Discussion

After the completion of engineering specifications, the results are the development of information that is required in designing and fabricating robot gripper manipulator. The requirements issued by customer are used as reference in developing the concepts that comply towards the requirements. Engineering targets list the technical requirements needed to produce a quality gripper. The target values are developed and used in the designing phase to achieve within minimum or maximum of these target values.

The overall specifications required for robot gripper can be summarized as in Table 3 below:

Table 3: Overall engineering specifications

No.	Specifications	Project Stages Utilization
1	Dimensions not exceed 1m length X 1m width X 1m height	Design
2	Total weight not exceed 10kg	Concept
3	2 workpieces shape, cube and cylinder	Concept
4	Minimum gripping force of 27.5N	Evaluation
5	Maximum gripping range of 800mm	Design
6	Maximum action times of 10s	Evaluation

No.	Specifications	Project Stages Utilization
7	Avoidance of damage to workpieces	Concept
8	Material and manufacturing availability	Manufacturing
9	Robot gripper autonomously controlled	Testing
10	Electrical connection via wired cable	Fabrication
11	Voltage for power supply not exceeding 24V	Testing

4.2 Develop Concept

This second stage is the development of concepts that uses understanding from some of the engineering specifications constructed previously. The concepts developed will consist of idea that is sufficient to evaluate the physical principles that govern its behavior. Developing concepts will consist of functional decomposition, generating concepts and evaluation.

4.2.1 Functional Decomposition

This technique used to decompose gripping problem into smaller parts in order to come out with understanding of functions required for gripping gripper and subsequently treating it as separate subsystem. The technique consists of 3 steps:

4.2.1.1 Step 1: Develop Overall Function

An overall function on basis of customer requirements is generated. The most important problem is to "conduct gripping manipulation". This problem is then put into a 'black box'. The function meanwhile can be associated with three main types of flow:

i. Thin line for energy flow ————
ii. Thick line for material flow ━━━━
iii. Dotted line for information flow ················

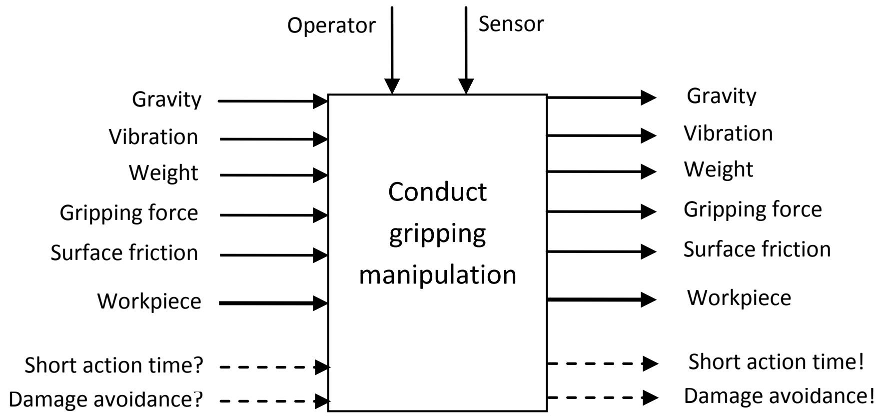


Figure 13: Gripper black box

The black box shows the energy or forces that interact in order to conduct gripping manipulation. The operator and sensor are external objects that interact with system. To successfully conduct gripping manipulation, the robot gripper needs to be able to avoid damage to workpiece and short action time for each cycle of the gripping manipulation.

4.2.1.2 Step 2: Create Subfunctions

This step is used to decompose the overall function into subfunctions. Each subfunctions have simple descriptions that are helpful in order to meet the requirements. For the subfunctions of "conduct gripping manipulation", there are 3 phases for the process which are:

i. Assembly phase

   This phase is executed during assembly of gripper parts. The assembled parts then need to be evaluated in its load stress and mechanism dynamics.

ii. Gripping phase

   Gripping phase has 2 functions that are detecting object or workpiece presence and in sequence, grasp the object.

iii. Lifting phase

Lifting is also included in the designing of gripper since it relate to behavior of gripper and needed for the prototype to perform competition task. Lifting phase has 2 functions that are to lift the gripper and detect the upper and lower limit of displacement of lifter which is called as ‘detect limit’.

Figure 14 below shows tree structure of decomposition of the overall function:

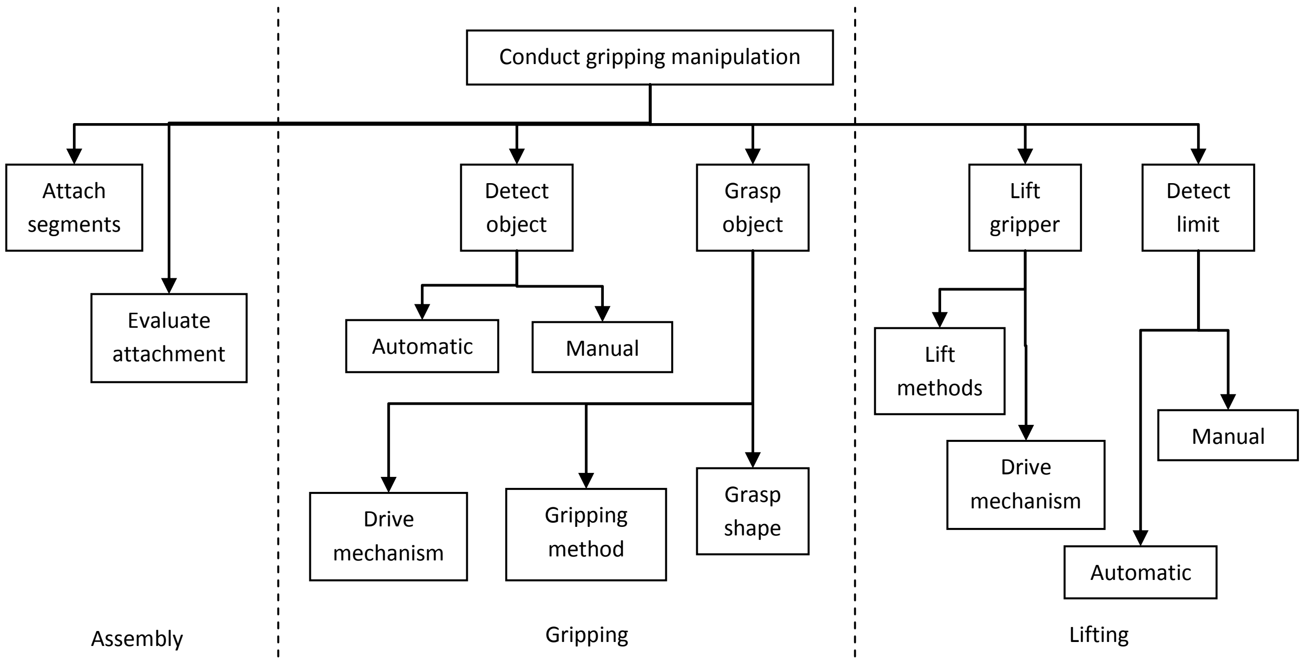


Figure 14: Tree structure of decomposition of the overall function

4.2.1.2 *Step 3: Order the Subfunctions*

After step 2, a more detail of functions needed for "conduct gripping manipulation" had been acquired. Each subfunctions are also listed with its corresponding details. This is details that are needed in creating concepts for each subfunctions. This next step is now used to order the sequence of each subfunctions above. Figure 15 below shows the order together with flow of material and energy into system.

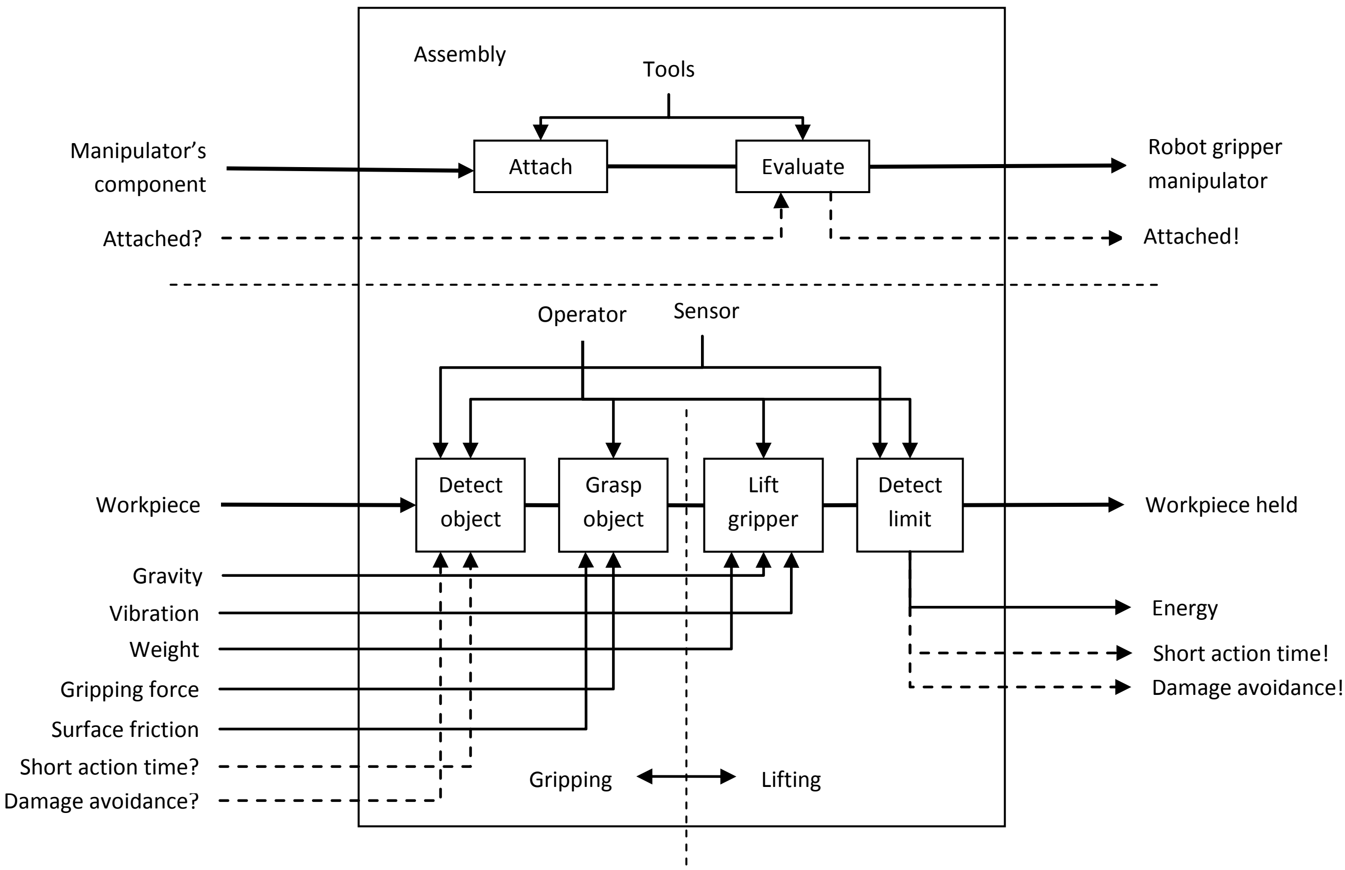


Figure 15: Subfunctions order together with flow of material and energy

4.2.2 Generating Concept

Concept generation will use the functions developed into concepts that satisfy them. The goal here is to develop as many concepts from each subfunctions. The concepts are then listed on Table 4 below:

Table 4: Concepts list

<table>
<tr><th colspan="2">Subfunctions</th><th colspan="3">Concepts</th></tr>
<tr><td colspan="2" rowspan="2">Attach segments</td><td>Mechanical fastener</td><td>Adhesive bonding</td><td>Weld</td></tr>
<tr><td>Brazing</td><td>Soldering</td><td></td></tr>
<tr><td colspan="2">Evaluate attachments</td><td>Gauge tools</td><td>Hand</td><td>Simulation</td></tr>
<tr><td colspan="2" rowspan="4">Detect object</td><td>Operator control</td><td>Proximity switch</td><td>Light sensor</td></tr>
<tr><td>Strain-gauge element</td><td>Potentiometer sensor</td><td>Capacitive element</td></tr>
<tr><td>Eddy current proximity sensors</td><td>Inductive proximity switch</td><td>Hall effect sensor</td></tr>
<tr><td>Optical encoders</td><td>Pneumatic sensors</td><td></td></tr>
<tr><td rowspan="5">Grasp object</td><td rowspan="3">Gripping method</td><td>Axial gripper</td><td>Radial gripper</td><td>Angle gripper</td></tr>
<tr><td>3 point gripper</td><td>Suction gripper</td><td>Permanent magnet</td></tr>
<tr><td>Electromagnet gripper</td><td></td><td></td></tr>
<tr><td>Drive mechanism</td><td>Electromechanical drives</td><td>Pneumatic drives</td><td>Hydraulic drives</td></tr>
<tr><td>Grasp shape</td><td>Friction grip</td><td>Encompassing grip</td><td>Concentric jaw</td></tr>
<tr><td rowspan="2">Lift gripper</td><td>Drive mechanism</td><td>Electromechanical drives</td><td>Pneumatic drives</td><td>Hydraulic drives</td></tr>
<tr><td>Lift methods</td><td>Vertical lifter</td><td>Angle lifter</td><td></td></tr>
<tr><td colspan="2" rowspan="4">Detect limit</td><td>Operator control</td><td>Proximity switch</td><td>Light sensor</td></tr>
<tr><td>Potentiometer sensor</td><td>Capacitive element</td><td>Eddy current proximity sensors</td></tr>
<tr><td>Inductive proximity switch</td><td>Optical encoders</td><td>Pneumatic sensors</td></tr>
<tr><td>Hall effect sensor</td><td></td><td></td></tr>
</table>

4.2.3 Evaluating Concept

After generating possible concepts for each subfunctions, each concepts are evaluated. Concept evaluation goal is to choose concepts developed previously into one that has the highest potential of meeting desired requirements. The method for evaluation will consist of 3 evaluation techniques:

i. Feasibility judgment
ii. Go / no-go screening
iii. Decision matrix

4.2.3.1 Feasibility Judgment

Feasibility judgment is technique used to determine feasibility of concepts in designing gripper. The judgment made is based on the references from handbooks. Several handbooks were referred such as in manufacturing, mechatronics and mechanism aspect of gripper.

The concepts are divided into 4 types of status which are 'feasible', 'not feasible', 'conditional', and 'worth considering'. From this status, 'not feasible' concepts are best to be discarded before move to next method. The discarded concepts are highlighted in red shaded cell. The reason column explains why the specific concepts are considered not feasible or conditional. Table 5 shows the feasibility judgment result:

Table 5: Feasibility judgment result

Subfunctions		Concepts	Feasibility Judgment	Reason
Attach segments		Mechanical fastener	Feasible	
		Adhesive bonding	Conditional	Weak to 'peeling'
		Weld	Feasible	
		Brazing	Conditional	Need specific type of joint
		Soldering	Not feasible	Weak strength
Evaluate attachments		Hand	Not feasible	Subjective measurement
		Gauge tools	Feasible	
		Simulation	Feasible	
Detect object		Operator control	Feasible	
		Proximity switch	Feasible	
		Infrared sensor	Conditional	Depend on response time
		Strain-gauge element	Not feasible	Can't detect object position
		Potentiometer sensor	Not feasible	Can't detect object position
		Capacitive element	Feasible	
Detect object		Eddy current sensors	Not feasible	Only detect conductive object
		Inductive switch	Not feasible	Only detect metallic object
		Optical encoders	Not feasible	Can't detect object position
		Pneumatic sensors	Worth considering	Require pneumatic system
		Hall effect sensor	Not feasible	Only detect magnetic object
Grasp object	Gripping method	Axial gripper	Feasible	
		Radial gripper	Feasible	
		Angle gripper	Feasible	
		3 point gripper	Worth considering	Shape limitation
		Suction gripper	Not feasible	Objects has rough surface
		Permanent magnet	Not feasible	Objects are plastics
		Electromagnet	Not feasible	Objects are plastics
	Drive mechanism	Electromechanical drives	Feasible	
		Hydraulic drives	Conditional	High cost, leaking risk
		Pneumatic drives	Feasible	
	Grasp shape	Friction grip	Worth considering	Low surface friction
		Encompassing grip	Conditional	Shape limitation
		Concentric jaw	Conditional	Only grip one shape

Subfunctions		Concepts	Feasibility Judgment	Reason
Lift gripper	Drive mechanism	Electromechanical drives	Feasible	
		Hydraulic drives	Conditional	High cost, leaking risk
		Pneumatic drives	Feasible	
	Lift methods	Vertical lifter	Feasible	
		Angle lifter	Worth considering	Complexity
Detect limit		Operator control	Feasible	
		Proximity switch	Feasible	
		Infrared sensor	Conditional	Depend on response time
		Potentiometer sensor	Not feasible	Not suitable for linear displacement
		Capacitive element	Feasible	
		Eddy current sensors	Conditional	For conductive objects
		Inductive switch	Conditional	For metallic objects
		Optical encoders	Feasible	
		Pneumatic sensors	Worth considering	Require pneumatic system
		Hall effect sensor	Feasible	

4.2.3.2 Go / No-go Screening

Go / no-go screening method uses customer's requirements to evaluate the concepts. Again the screening made is based on the references from handbooks. A 'go' means that the concept can fulfill the requirement and vice versa for 'no-go'. The discarded concepts are highlighted in red shaded cell. Empty slots means that the concept and requirement are not related. Table 6 below shows the go / no-go screening:

Table 6: Go / no-go screening result

Subfunctions		Concepts	Customer's Requirement: Small gripper structure	Options for different workpiece shape	Optimum gripping force	Low links and joints	Low mass	Avoidance of damage	Short action times	Material / manufacturing availability
Attach segments		Mechanical fastener	Go			Go	Go			Go
		Adhesive bonding	Go			Go	Go			Go
		Weld	No			Go	Go			Go
		Brazing	Go			Go	Go			No
Detect object		Operator control							Go	Go
		Proximity switch							Go	Go
		Light sensor							Go	Go
		Capacitive element							Go	No
		Pneumatic sensors							Go	No
Grasp object	Gripping method	Axial gripper	Go	Go				Go		
		Radial gripper	Go	Go				Go		
		Angle gripper	Go	Go				Go		
		3 point gripper	Go	No				Go		
	Drive mechanism	Electromechanical drives			Go		Go		Go	Go
		Hydraulic drives			Go		No		Go	Go
		Pneumatic drives			Go		Go		Go	Go
Grasp object	Grasp shape	Friction grip	Go	Go	Go	Go		Go		
		Encompassing grip	Go	Go	Go	Go		Go		
		Concentric jaw	Go	No	Go	Go		Go		
Lift gripper	Drive mechanism	Electromechanical drives					Go		Go	Go
		Hydraulic drives					No		Go	Go
		Pneumatic drives					Go		Go	Go
	Lift methods	Vertical lifter	Go			Go	Go			
		Angle lifter	Go			Go	Go			

Subfunctions	Concepts	Customer's Requirement							
		Small gripper structure	Options for different workpiece shape	Optimum gripping force	Low links and joints	Low mass	Avoidance of damage	Short action times	Material / manufacturing availability
Detect limit	Operator control							Go	Go
	Proximity switch							Go	Go
	Infrared sensor							No	Go
	Capacitive element							Go	No
	Eddy current sensors							Go	No
	Inductive switch							Go	No
	Optical encoders							Go	Go
	Pneumatic sensors							No	No
	Hall effect sensor							Go	No

4.2.3.3 Decision Matrix

The final selection methods, is also known as evaluation matrix. Using this method, the final concepts will be selected through its score value to form the design that will yield the highest quality and most suit the customer requirements. Decision matrix is conducted by initially giving a ranking and subsequently weightage value to each customer's requirements. For each functions, a datum is chosen on one subfunctions. Other subfunctions then is compared with the datum. Better subfunctions are given '+' while less desirable subfunctions are given '-'. Equal quality subfunctions with datum are given 'S'. Then total score are computed according to its '+' and '-' with factor to the weightage. The discarded concepts are highlighted in red shaded cell. Empty slots means that the concept and requirement are not related. The decision matrix result is as in table 7:

Table 7: Decision matrix

Concepts			Small gripper structure	Options for different workpiece shape	Optimum gripping force	Low links and joints	Low mass	Avoidance of damage	Short action times	Material, manufacturing availability	**Overall total**	**Weighted total**
			Customer's Requirements									
		Weightage	8	7	6	1	3	2	4	5		
Attach Segments		Mechanical fastener	D			A	T			U		M
		Adhesive bonding	S			-	+			-	**-1**	**-3**
Detect Object		Operator control						D	A	T	U	M
		Proximity switch							+	S	**+1**	**+4**
		Light sensor							-	S	**-1**	**-4**
Grasp Object	Gripping method	Axial gripper	D	A				T			U	M
		Radial gripper	+	S				S			**+1**	**+8**
		Angle gripper	-	S				S			**-1**	**-8**
	Drive mechanism	Electromechanical drives			D		A		T	U		M
		Pneumatic drives			S		-		+	-	**-1**	**-4**
	Grasp shape	Friction grip	D		A	T		U				M
		Encompassing grip	S	-	S	S		S			**-1**	**-7**
Lift Gripper	Drive mechanism	Electromechanical drives					D		A	T	U	M
		Pneumatic drives					-		+	-	**-1**	**-4**
	Lift method	Vertical lifter	D			A	T				U	M
		Angle lifter	-			-	+				**-1**	**-6**
Detect Limit		Operator control						D	A	T	U	M
		Proximity switch							+	S	**+1**	**+4**
		Optical encoder							+	-	**0**	**-1**

4.2.4 Concepts Development Results and Discussion

Concept development had gone through 3 stages of selection and elimination. As the completion of decision matrix method, clearer and more objective information had been obtained in order to select the most suitable concept for robot gripper. Each subfunctions have its concepts that will be used for the design. From the decision matrix result, the final concepts for design of robot gripper can be listed. Table 8 below shows the final concepts selected:

Table 8: Final concepts

Functions		Final Concepts
Attach Segments		Mechanical fastener
Analyse Segments		Tools
		Simulation
Detect Object		Proximity switch
Grasp Object	Gripping method	Radial gripper
	Drive mechanism	Electromechanical drives
	Grasp shape	Friction grip
Lift Gripper	Actuation	Electromechanical drives
	Lift method	Vertical lifter
Detect Limit		Proximity switch

4.3 Develop Design

After the completion of concept development phase, design phase can now be developed. Design phase consist of 2 main stages which are generating design and evaluating design. Generating design stage is divided into 3 subphases, which are form generation, drawings development and material selection. Evaluating design stage meanwhile consists of mechanism analysis simulation software. Design phase may be regarded as phase where the physical shape of the robot gripper is developed. The first stage in design phase as indicated is the form generation:

4.3.1 Form Generation

Form generation is done during the construction of layout drawing. Layout drawing is the working sketch drawing made during initial designing progress. Form generation has 4 elements, in which all these elements are considered during layout drawing constructions. The elements are:

i. Constraints – dimension limitations is identified and design must not exceed the limit.
ii. Configure components – components are separated into different task to determine its location and orientation.
iii. Connections – components defined above will be determined in terms of their relative position for connections.
iv. Components – this to determine the components shape and parts to do its task.

The completed layout drawings consist of 4 segments shown as in figure 16 to 19:

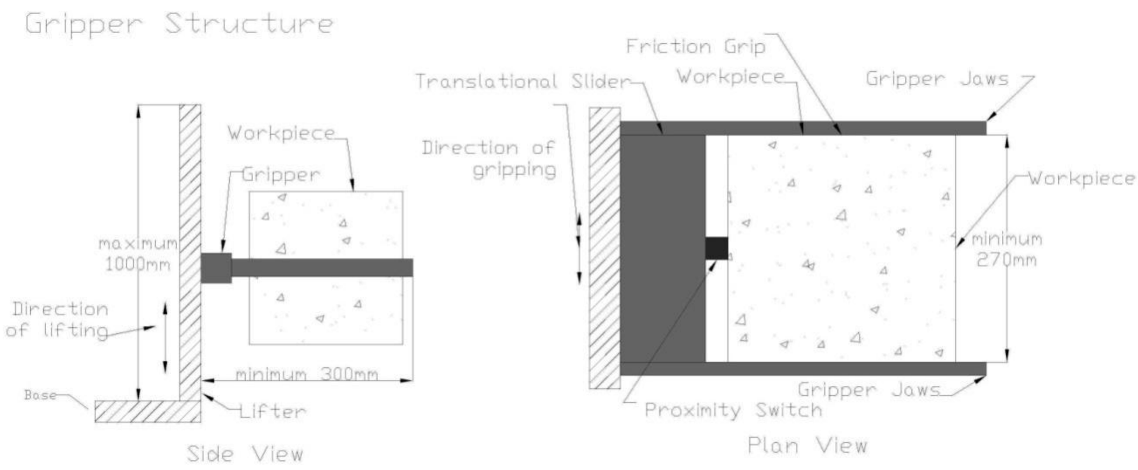


Figure 16: Gripper structure layout drawing

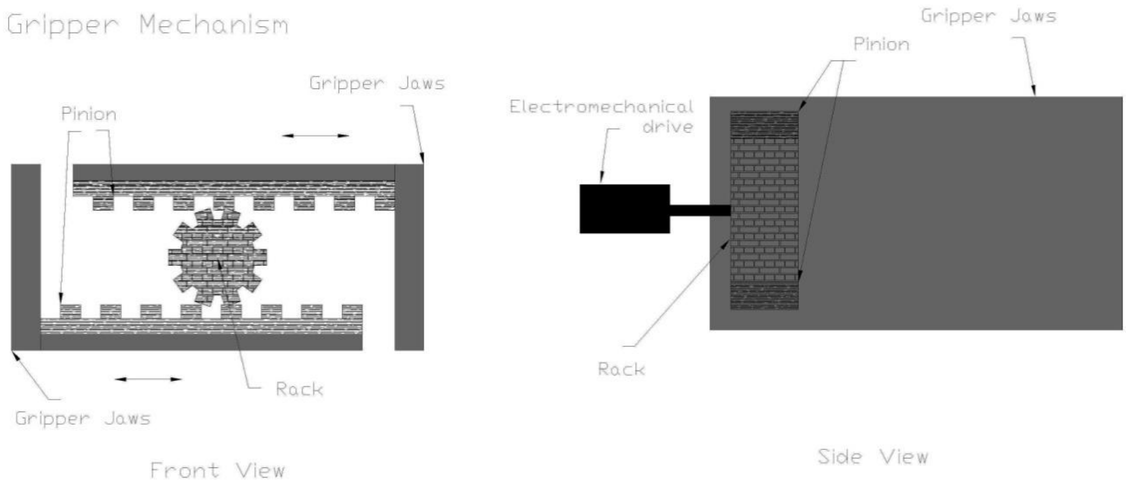


Figure 17: Gripper mechanism layout drawing

4.3.1.1 Gripper Layout Drawing Discussion

i. Constraints – gripping range is from 500mm to 150mm to give wide opening as well as secure gripping.

ii. Configure components – gripper is divided into gripper jaws, sliding parts and rack and pinion actuation.

iii. Connections – gripper jaws mounted on slider and added rubber grip at workpiece contact, rigid parts are attached to lifter.

iv. Components – implement rack and pinion mechanism using timing belt to avoid slipping during retraction of gripper jaws and proximity switch to detect workpiece orientation inside jaws.

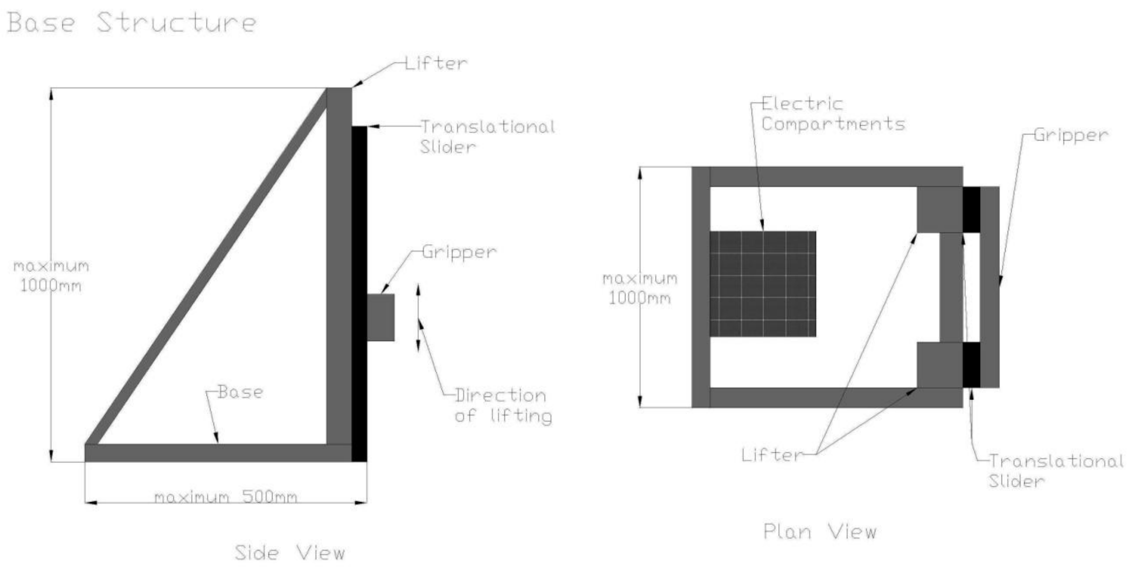


Figure 18: Base and lifter structure layout drawing

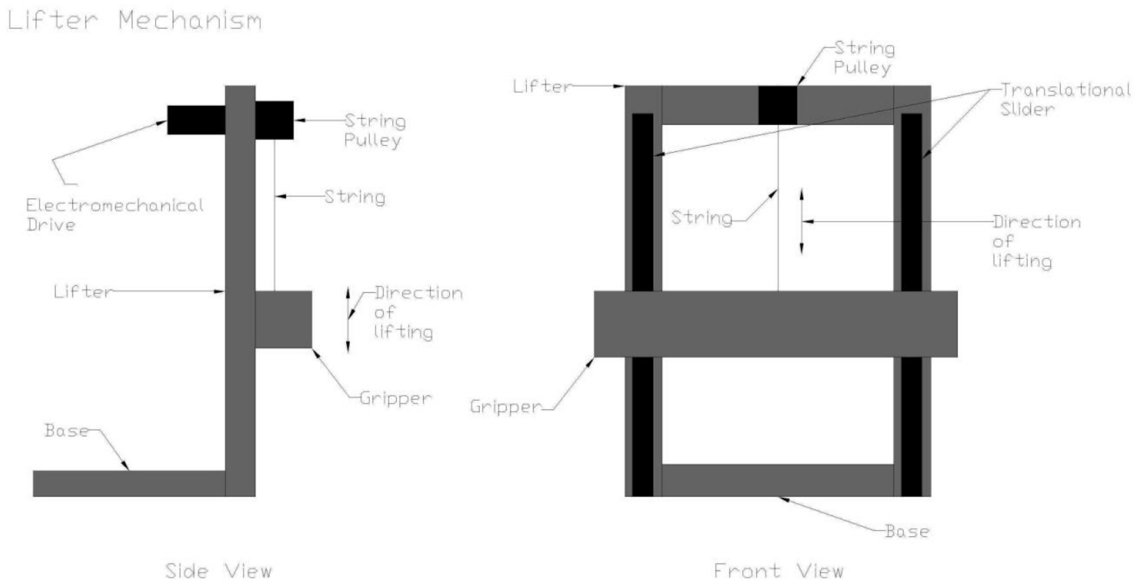


Figure 19: Lifter mechanism layout drawing

4.3.1.2 Base and Lifter Layout Drawing Discussion

i. Constraints – lifting range is from ground to 500mm and base dimension is around 500mm in both length and width.
ii. Configure components – base is divided into lifter support and parts compartment while for lifter are slider, pulley and strings actuation and lifting pole.

iii. Connections – whole of gripper is mounted on lifter slider and strings are attached to gripper for lifting.
iv. Components – lifter base is already pre-built by previous ROBOCON team activity and proven to be working. Base is extended to the back of gripper to provide counterweight.

4.3.2 Drawings Development

The layout drawings built were then used to construct the technical drawings of the gripper design. This technical drawing follows the design specifications and design concepts. The drawings drawn using AutoCAD application consist of the robot gripper part and both gripper and lifter assembled together.

4.3.2.1 Gripper Part Drawing

Figure 20 shows the 3 dimensional drawings of the gripper parts in default or initial position. Noted that the gripper jaws can be maximize and minimize. The technical drawings for the gripper is shown in appendix ii. Figure 21 shows the maximum length of extension of the gripper:

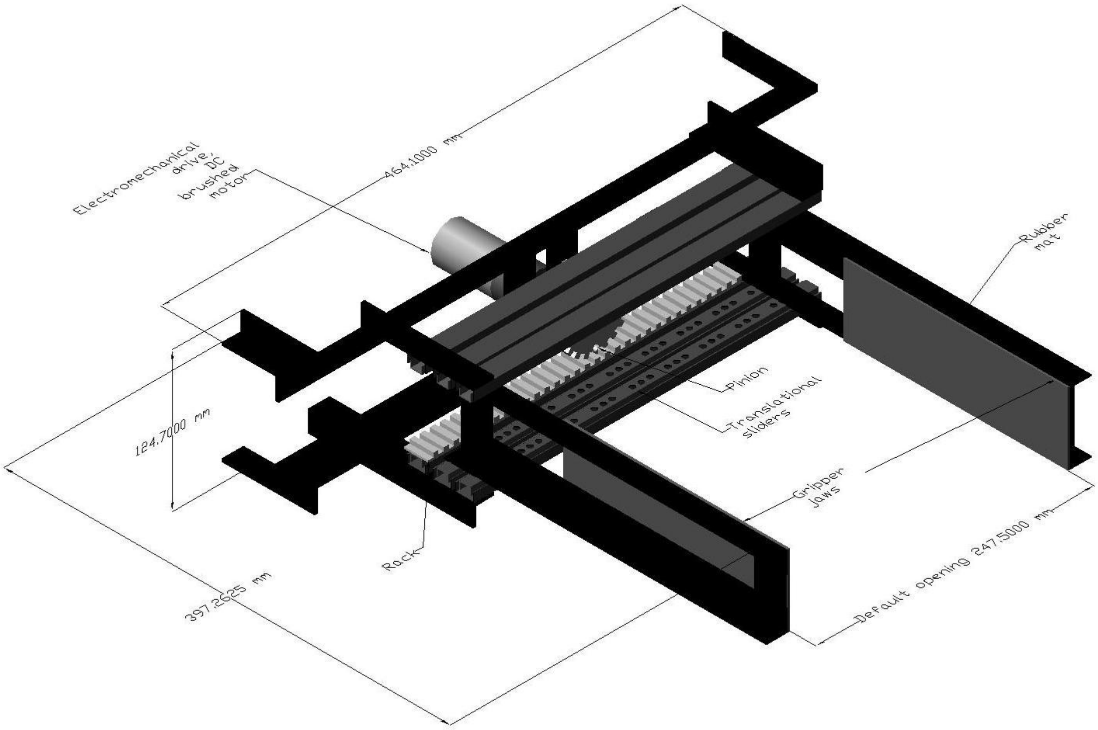


Figure 20: Gripper parts drawing in default position

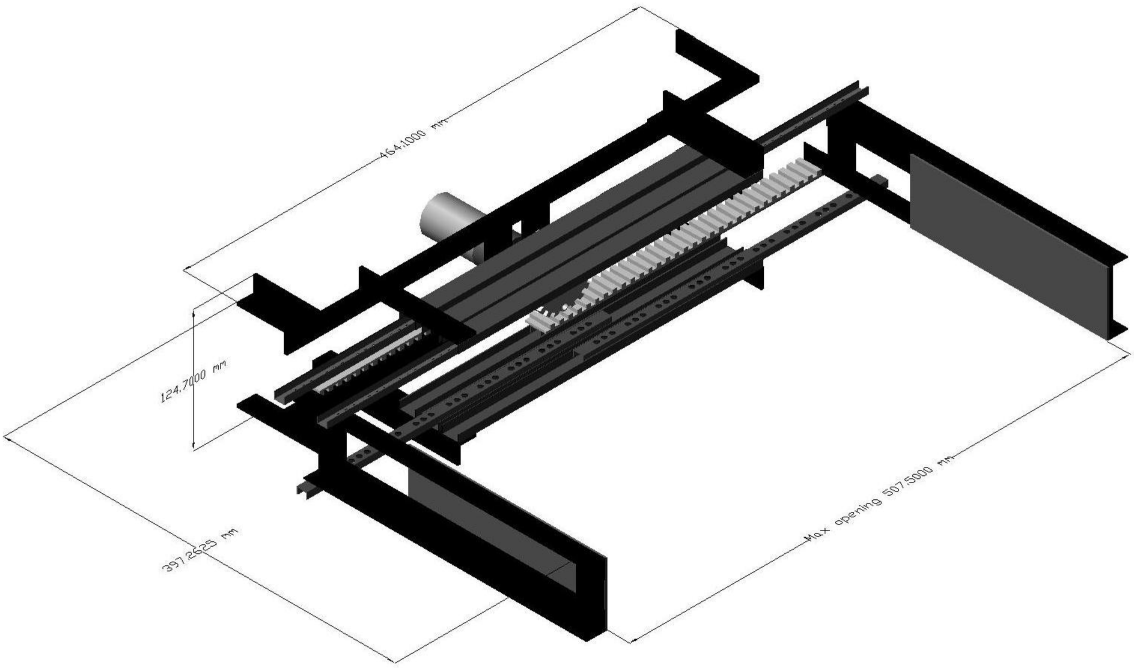


Figure 21: Gripper parts drawing in maximum position

4.3.2.2 Lifter and Gripper Part Drawing

Figure 22 shows the 3 dimensional drawings of the gripper parts combined with the lifter and the base. The gripper position is placed at its minimum or at ground level. The maximum position of the gripper height meanwhile is shown in Figure 23.

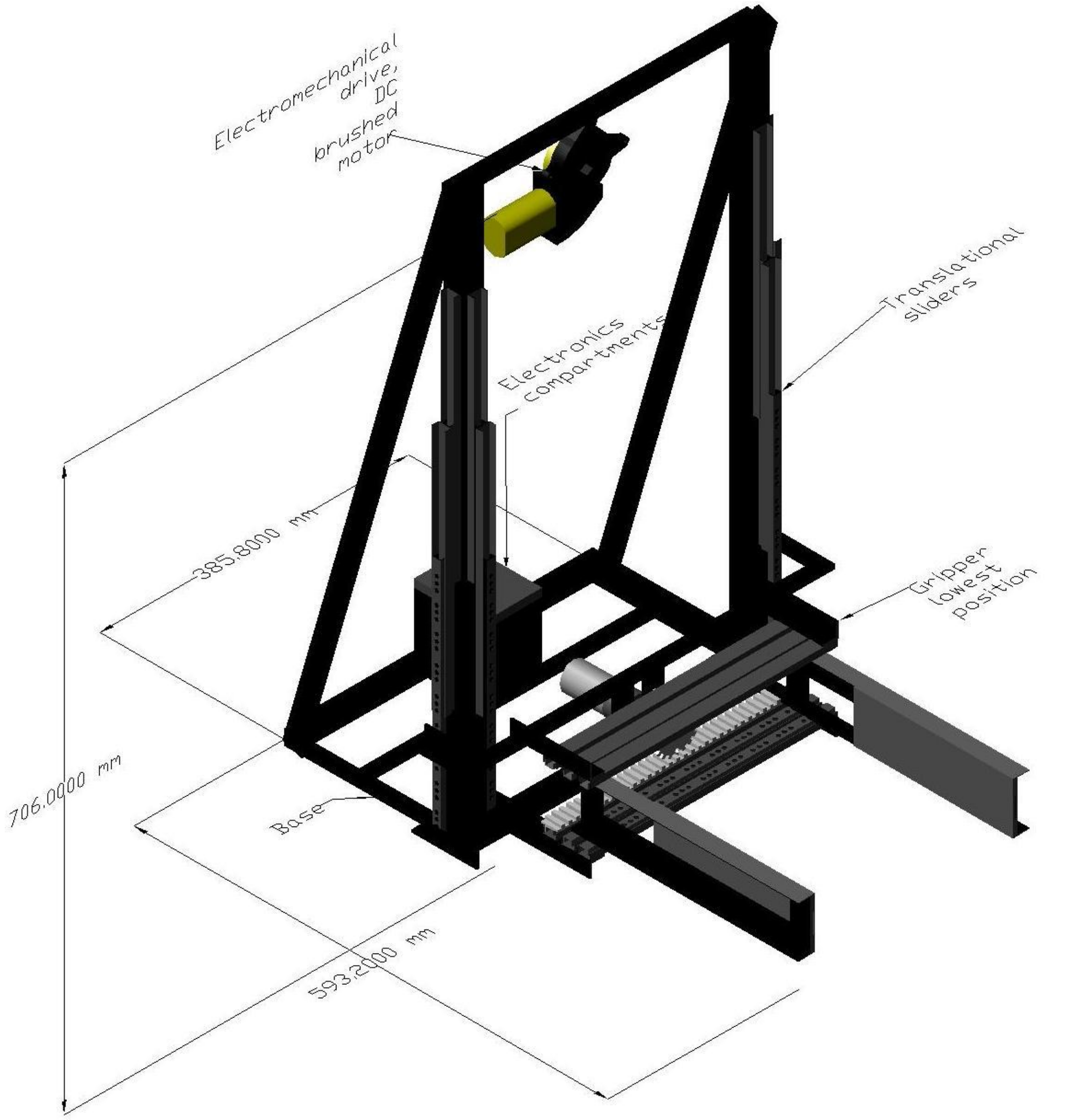


Figure 22: Combined parts drawing in lowest position

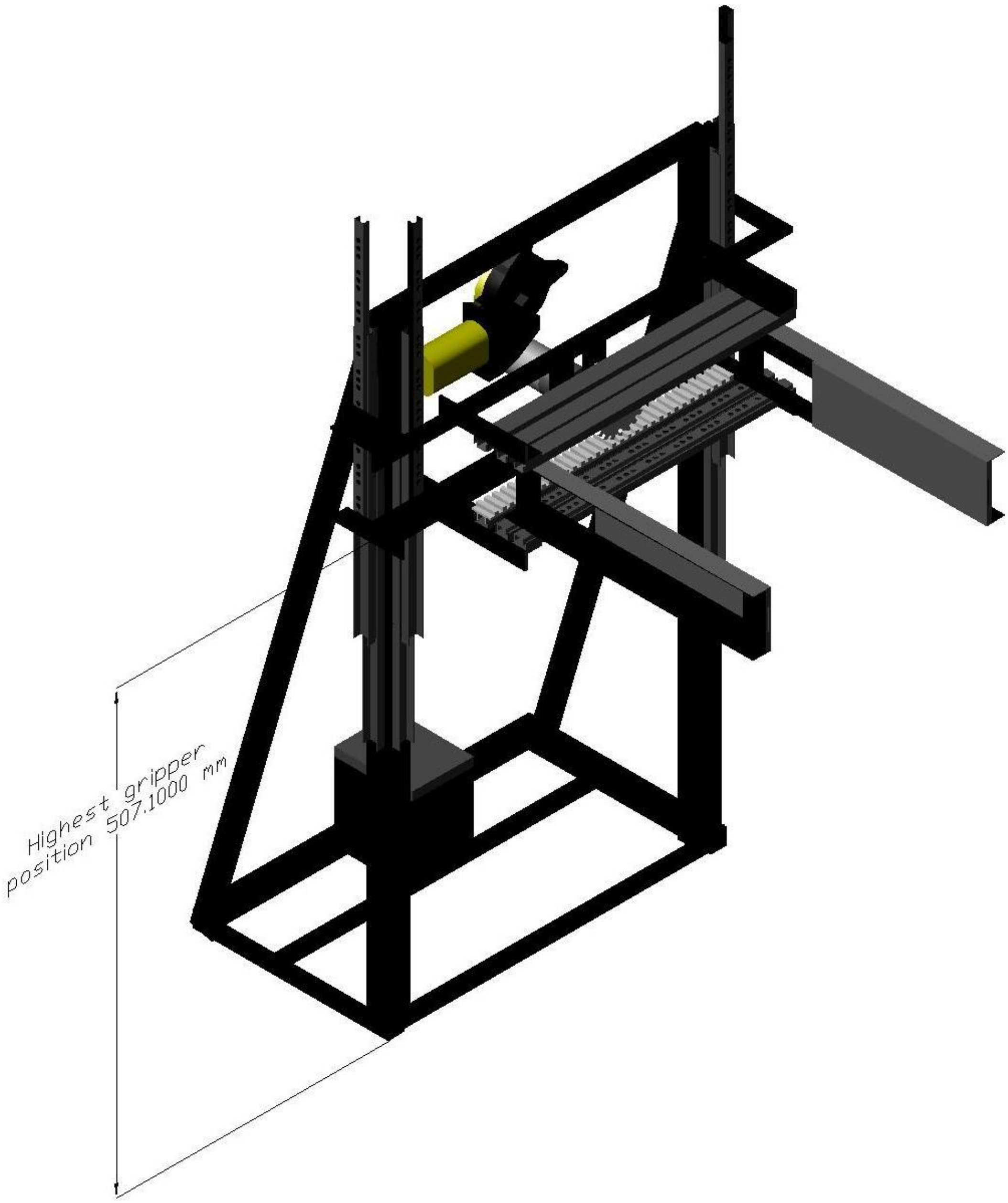


Figure 23: Combined parts drawing in highest position

4.3.3 Material Selection

Material selection here is crucial in order to identify material properties to be used and warrant further evaluation of gripper design on finite element analysis. Some parts in the gripper such as rack, pinion and slider are obtained from market parts. Material selection used here is using the approach of material selection before manufacturing process selection. The outcome of material selection is the selection of most suitable material to be used for the robot gripper structure. Approach of material selection here consists of 3 steps:

4.3.3.1 Determine Important Material Properties

Material properties are determined from the functions needed for the design of robot gripper. Table 9 shows the functions and results of its corresponding material properties:

Table 9: Important material properties [11]

Functions	Material Properties
Low mass	Density
Exhibit elastic deformation	Yield strength
Minimal deflection	Elongation
Avoidance of plastic deformation	Yield strength
Able to withstand sudden impact	Hardness
Low material cost	Price
Ease of manufacturing	Machinability

4.3.3.2 Compare Properties with Database

Database containing wide range of material and its properties are obtained. Some of the selected materials are listed below. Then preliminary screening then was made to determine candidate materials that fit for the functions.

Discarded materials were mainly due to its properties, shown in red cells did not either meet or close to the required functions. Table 10 shows the screening process of materials:

Table 10: Screening of Material [11]

Material	Material Properties						Status
	Density $(\frac{lb}{in^3})$	Yield Strength (MPa)	Elongation (%)	Hardness (HV)	Machinability Index (Annealed)	Price per pound	
Polyethylene (PE)	0.034	13	600	-	-	0.30	Discard
Nylon (PA)	0.042	62	27	-	-	3.00	Discard
Carbon Steel (1010)	0.28	275	35	110	100	0.40	Accept
Stainless Steel (430)	0.28	275	20	260	165	1.25	Accept
Aluminum Alloy (1100-H14)	0.098	117	9	26	180	0.73	Accept
Copper Alloy (C11000)	0.323	344	4	60	150	0.92	Accept
Nickel Alloy (N02200)	0.321	186	50	170	340	5.30	Discard

4.3.3.3 Investigate Candidate Material in Greater Detail

In order to select the final material, weighted property index method is used. One material is selected as the datum and other materials are compared. 'S' value means the properties are relatively same with datum. '+' show it is better than datum and '−' shows it is worse than datum. Table 11 below shows the method in selecting the final material [12]:

Table 11: Weighted Property Index Method for Material Selection [12]

Materials	Density ($\frac{lb}{in^3}$)	Yield Strength (MPa)	Elongation (%)	Hardness (HV)	Machinability Index (Annealed)	Price per pound	**Overall total**	**Weighted total**
Weightage	5	1	4	2	4	5		
Carbon Steel (1010)	0.28 D	275	35 A	110 T	100	0.40 U	**0**	**0**
Stainless Steel (430)	0.28 S	275 S	20 S	260 +	165 +	1.25 -	**+2**	**+1**
Aluminum Alloy (1100-H14)	0.098 +	117 -	9 +	26 -	180 +	0.73 -	**0**	**+5**
Copper Alloy (C11000)	0.323 -	344 +	4 +	60 -	150 +	0.92 -	**0**	**-3**

From Table 6 above, copper and carbon steel has about the same score. Meanwhile for stainless steel, the score is slightly higher and aluminum gave the highest marks. Aluminum alloy has very low density thus giving lightweight parts, relatively good yield strength, small elongation due to stress, good machinability and high corrosion resistant. Thus it is best to select aluminum alloy 1100-H14 as the final material to be used.

4.3.4 Design Evaluation

This final stage for design development is the evaluation of the gripper design. This evaluation will consist of analysis of dynamic mechanism. Design evaluation also act as part of the secondary objective for project. There are 2 types of analysis conducted, which are selection of electric motor specifications using analytical method and dynamic mechanism analysis using ADAMS software.

4.3.4.1 Determine Electric Motor Specifications

Electric motor specifications are important to be determined to satisfy the required gripping force and power supply. Properties of motor that to be determined are type of motor, torque output, speed and operating voltage:

i. Motor type:
As recommended by ROBOCON advisor and by references to handbook, suitable type of motor is DC brushed motor type. This is because DC brush motor has relatively high speed, high torque, and easy to programmed.

ii. Torque required:
Minimum gripping force, F is 27.5 N
Pinion diameter, d is 55mm
Minimum torque required is:

$$T_{min} = F.\frac{d}{2} = 27.5N \times \frac{0.055m}{2} = 0.756Nm$$

iii. Required speed:

Since lifter for the robot gripper is pre-built, testing has been done and time taken for lifting is averaging 4 s

Maximum action time is 10 s

Maximum time left, t for gripping is 6 s

Gripping range for each jaw, d is 150 mm

Linear velocity for gripper jaw:

$$v = \frac{d}{t} = \frac{0.15m}{6s} = 0.025m.s^{-1}$$

Minimum angular velocity, ω_{min} for pinion and motor:

$$\omega_{min} = \frac{v}{r} = \frac{0.025m.s^{-1}}{0.0275m} = 0.91rad.s^{-1} = 8.68\,rpm$$

iv. Operating voltage:

Maximum operating voltage is 24V

By referring to these specifications, most suitable motor is selected. The selected motor specifications are as follows:

i. Motor type = DC brushed motor
ii. Torque output = 1.1 Nm > T_{min}
iii. Motor speed = 30 rpm > ω_{min}
iv. Operating voltage = 12V < V_{max}

4.3.4.2 *Dynamic Mechanism Analysis*

Dynamic mechanism analysis is performed using ADAMS simulation software. The outcome of this analysis is mainly to estimate action time taken for robot gripper to successfully grip the workpiece. The model for analysis consists of both gripper jaws and the gripper base as 'ground'. By referring to motor specifications, the model was constructed and simulated as in figure 24 and 25:

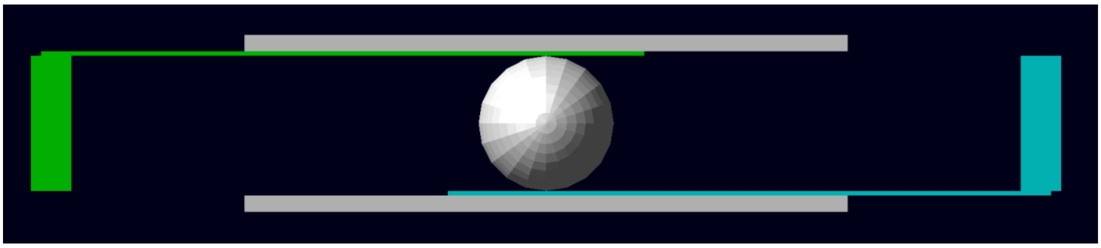


Figure 24: ADAMS model gripper jaw opening

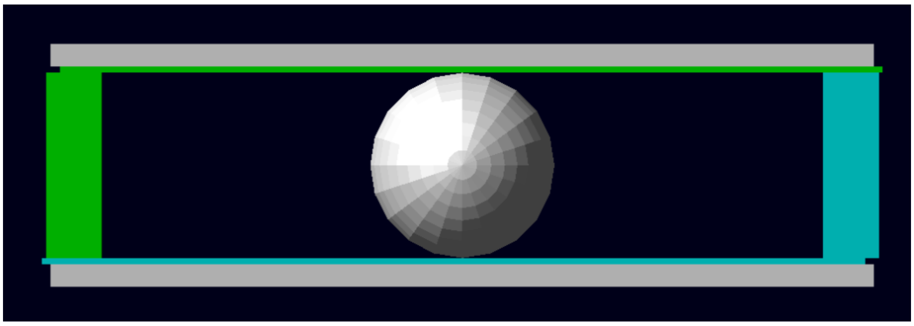


Figure 25: ADAMS model gripper jaw closing

The model was viewed from front perspective. The green part is the right gripper jaw, blue part is the left gripper jaw, gray part is the gripper base and round part is the pinion. Both gripper jaws are retracted towards the pinion for displacement length of 150mm. The result of simulation is the gripper jaw displacement length vs. time taken as in figure 26 below:

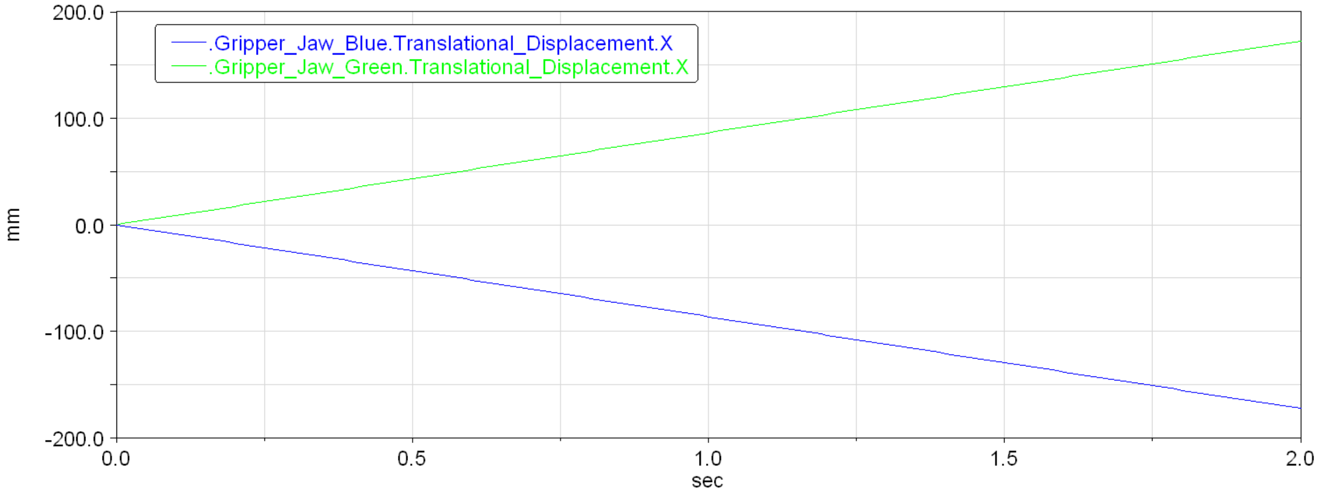


Figure 26: Gripper jaws translational displacement graph

By referring to figure 26, both gripper jaw has same velocity and thus lead to synchronize displacement rate. Since the required displacement length is 150mm, time taken is estimated to be 1.75 seconds. Comparing to 6s available time for gripping, the gripper has much faster gripping speed than targeted.

4.3.5 Design Development Results and Discussion

Through the design development phase, several major results had been obtained. Design development followed by its evaluation has resulted in a feasible design for the prototype to be fabricated. In design development, 3 results had been obtained while for design evaluation, 2 results had been obtained. The results are listed as in table 12 below:

Table 12: Design phase results

<table>
<tr><th>Design Stages</th><th>Design Sub-phases</th><th>Result</th></tr>
<tr><td rowspan="4">Develop design</td><td rowspan="2">Form generation</td><td>Layout drawings of robot gripper structure and mechanism</td></tr>
<tr><td>Layout drawings of robot base structure and lifter mechanism</td></tr>
<tr><td>Drawings development</td><td>CAD drawings of assembled gripper, lifter and base lowest and highest position</td></tr>
<tr><td>Material selection</td><td>Selected aluminum as the material for robot gripper and base structure</td></tr>
<tr><td rowspan="2">Evaluate design</td><td>Electric motor specifications</td><td>Use DC brush motor, torque output 1.1Nm, speed 30 rpm and operating voltage at 12V</td></tr>
<tr><td>Dynamic mechanism simulation</td><td>Estimated gripping time of 1.75 s, within target time.</td></tr>
</table>

4.4 Manufacturing Processes

In this part, the constructed and evaluated design will be transformed into a prototype model of the gripper. The first process in order to construct the prototype is to perform designs for manufacturing. Next is manufacturing process selection.

4.4.1 Design for Manufacture

Design for manufacture is important for this project. Since the ultimate objective of project is to construct a prototype, design for manufacture help to prepare paperwork and guidance during fabrication process. Design for manufacture consists of two tasks, which are preparation of assembly drawings and followed by bill of materials.

4.4.1.1 Assembly Drawings

Assembly drawings are essential for fabrication process. The drawings provide exploded view for guidance during fabrication and assembly of prototype.

Assembly drawings are constructed by referring to design developed from previous phase. It shows type of joint used for specific parts as well as type of material used. Figure 27 shows the overall assembly drawings for robot gripper. The rest of assembly drawings are enclosed in appendix (ii).

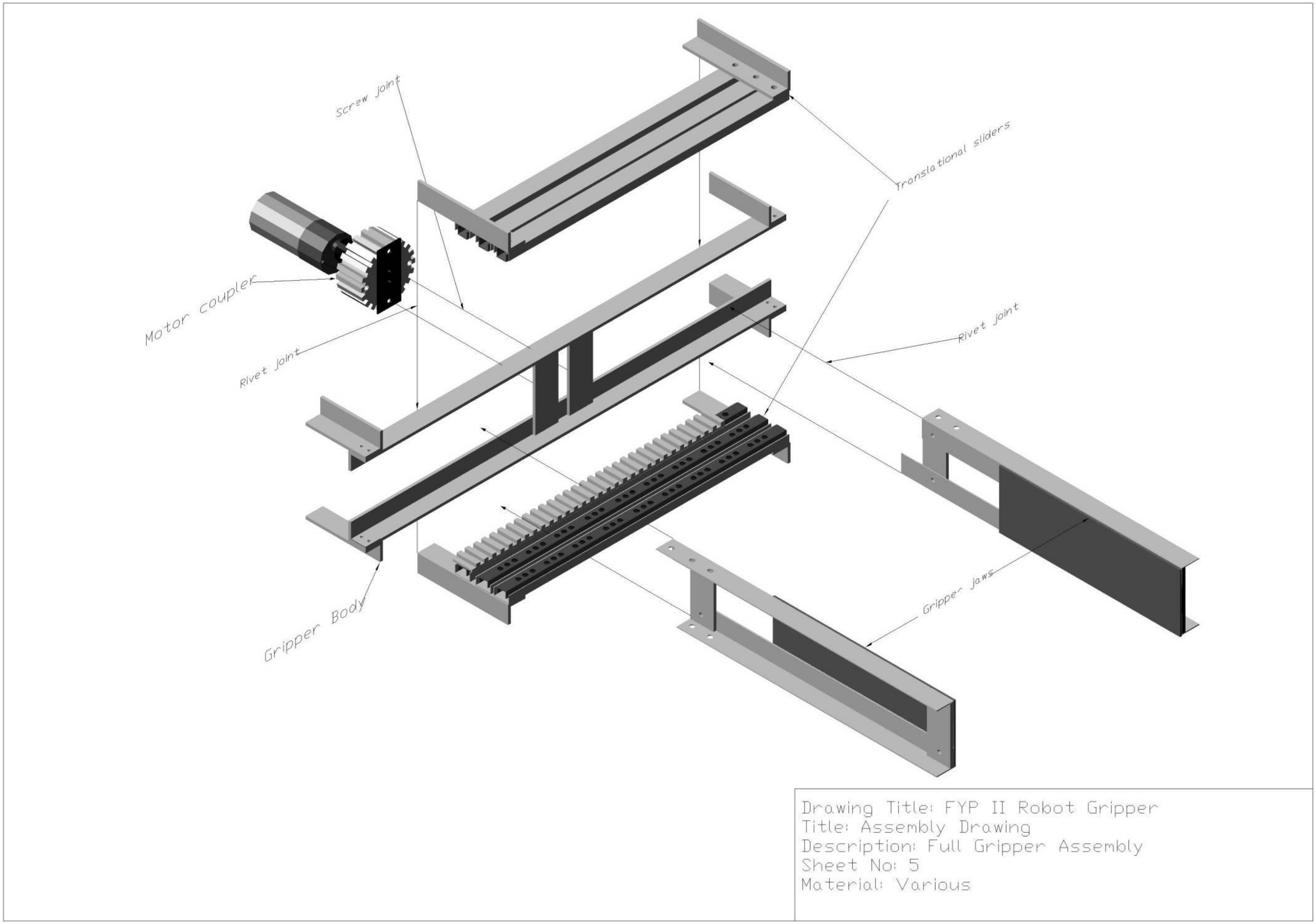


Figure 27: Full robot gripper assembly drawings

4.4.1.2 Bill of Materials

Bill of materials can be regarded as simplified assembly drawings. The function is to list all materials and components that are needed for the construction of the prototype. Bill of materials is obtained from the assembly drawings. Bill of material for robot gripper prototype is shown in the table 13 below:

Table 13: Bill of materials

Parts	Material	Quantity
Gripper jaws	Various shape aluminum	2 (pair)
	Rubber mat	2
Translational slider	L bar shape aluminum	4
	Mild steel translational slider	6
	Polymer rack	2
Gripper body	Various shape aluminum	2 (pair)
Motor-pinion coupler	Aluminum plate	1
	DC motor	1
	Mild steel pinion	1
	Aluminum coupler	1

4.4.2 Manufacturing Process Selection

The final phase before fabrication of prototype is to select suitable manufacturing processes for each part in the bill of materials. Possible manufacturing processes are listed. Then the most suitable manufacturing processes are evaluated by referring to handbook on manufacturing process selection. Table 14 shows the list of possible manufacturing processes. Red highlighted cells are discarded.

Table 14: Evaluation on manufacturing processes

Material	Possible Manufacturing Processes	Feasibility Evaluation
Various shape aluminum	Casting	Require several more finishing and large equipments, wide tolerance
	Sawing (market parts)	Suitable to remove bulk material volume, market parts had pre-shaped aluminum bar
	Sheet metal forming	Suitable for thin metal plate
Rubber mat	Market part	-
Mild steel translational slider	Market part	-
Polymer rack	Market part	-
DC motor	Market part	-
Mild steel pinion	Market part	-
	Gear manufacture by machining	Require several phases and equipments, expertise in gear manufacture needed
	Electric discharge machining	Relatively slow production
Aluminum coupler	Turning	Conventional turning available, require less skilled labor
	Electric discharge machining	Relatively slow production

From table above, manufacturing process for various aluminum shapes is sawing from market parts. Aluminum coupler is manufactured by turning process. Meanwhile, other parts are obtained from market parts.

4.4.2 Manufacturing Process Results and Discussion

Through the design for manufacture phase, 2 outcomes had been obtained which are:

i. Construction of assembly drawings
ii. Bill of materials.

Both these data will be used in fabrication process. Another outcome is the selection of manufacturing process. Table 15 below shows the result of manufacturing process selection:

Table 15: Manufacturing process selection results

Material	Manufacturing Processes
Various shape aluminum	Sawing (market parts)
Rubber mat	Market part
Mild steel translational slider	Market part
Polymer rack	Market part
DC motor	Market part
Mild steel pinion	Market part
Aluminum coupler	Turning

4.5 Fabrication of Prototype

Fabrication prototype is the part in which the design developed and manufacturing process selected earlier is then transformed into a working prototype model of a robot gripper. Fabrication of the prototype consists of manufacturing of each single part for the robot gripper followed by assembly of parts. The completed prototype is then tested and results are compared with engineering specifications.

4.5.1 Manufacture Parts

Initial stage of robot gripper fabrication is the manufacturing of each part. Structure of the gripper is constructed from aluminum. The structure has mainly ‘L’ shape aluminum obtained from market and sawed as according to required length. Some parts are obtained entirely from market. Meanwhile the coupler for the motor-pinion joint is manufactured by turning process.

4.5.2 Assemble Parts

After parts had been manufactured, it is then assembled together to form the final product. Assembly of the prototype’s parts is performed by referring to assembly drawing developed during design phase. The prototype of the robot gripper mainly consists of:

i. Gripper jaws.
ii. Translational sliders.
iii. Rack and pinion.
iv. Electric motor.
v. Gripper base.
vi. Proximity sensor.
vii. Rubber mat.

4.5.3 Prototype Completion and Testing

Completed prototype of robot gripper is shown as in figure 28 below:

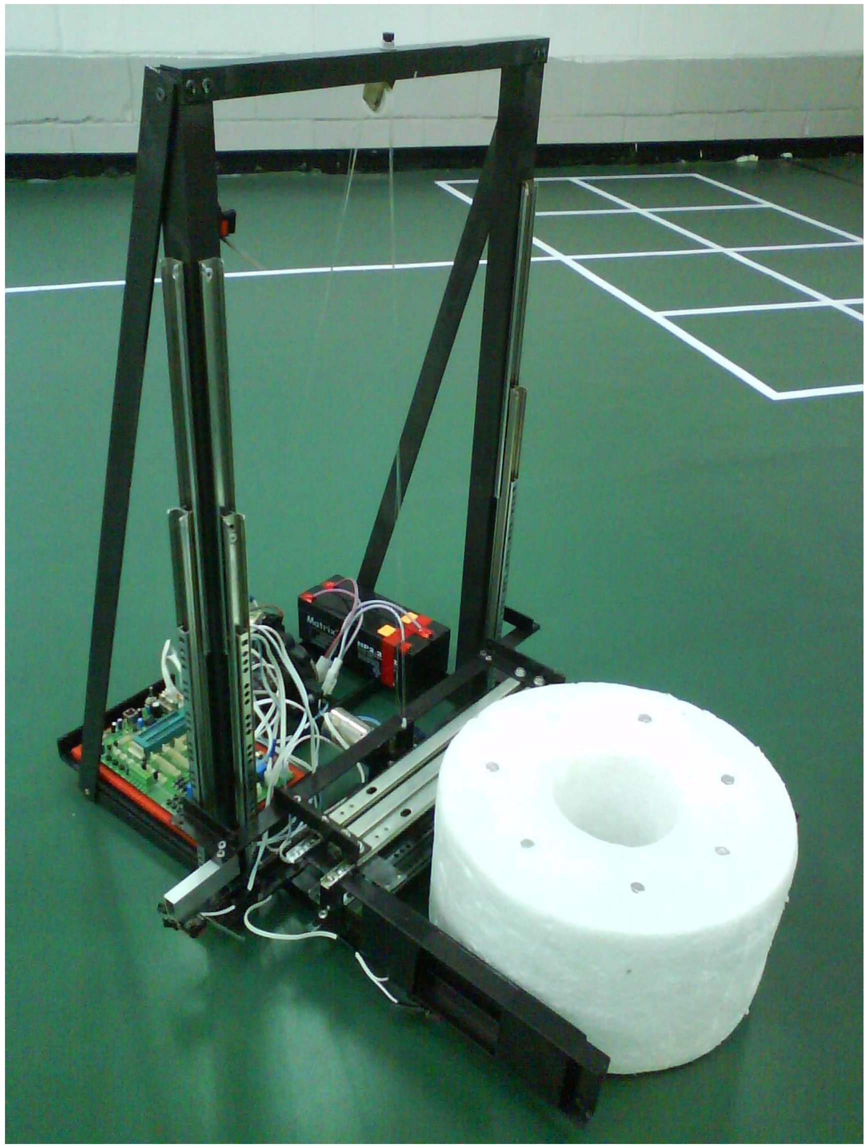


Figure 28: Completed prototype with workpiece

The prototype shown consists of lifter and gripper together with attached control board for the prototype to be able to operate. Details on the prototype are shown as in from figure 29 to figure 32 below:

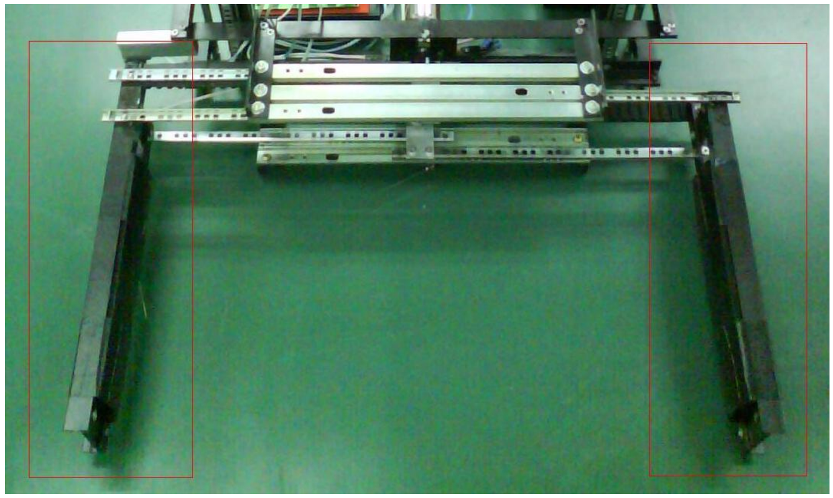


Figure 29: Prototype gripper jaws at maximum opening

Figure 30: Prototype rack, pinion and translational sliders

Figure 31: Prototype DC brush motor

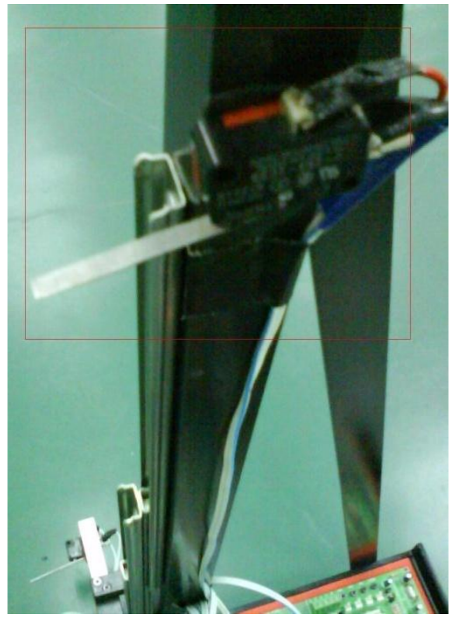


Figure 32: Prototype proximity switch

Method of operation of the robot gripper prototype is described as follows:

i. Workpiece is feed into gripper jaws opening.
ii. Workpiece touches with the first proximity switch.
iii. First proximity switch detect presence of workpiece and gripper jaws retract to grip the workpiece.
iv. Second proximity switch hit with workpiece and gripper jaws stop. At this condition the workpiece is tightly gripped.
v. Lifter pulley pulls the gripper upwards.
vi. Gripper hit with third proximity switch at 500mm above ground and lifter stop pulling upwards.
vii. The gripper remains idle for required duration.
viii. Lifter pulley pulls the gripper downwards.
ix. Gripper hit with fourth proximity switch at ground level and lifter stop pulling downwards.
x. Gripper jaws retract towards loosening workpiece and hit fifth proximity switch at 150mm jaws opening.
xi. Sequence is ready to be repeated again.

4.5.4 Prototype Results and Discussion

The gripping task was repeated 10 times. However, only 5 are successful due to unreliability of proximity switches. Result for the action time taken is shown as in table 16 below:

Table 16: Prototype testing timing results

Task No.	Time for Gripping (s)	Time for Lifting (s)	Total Time (s)
1	2.1	4.8	6.9
2	1.9	4.9	6.8
3	2.1	4.5	6.6
4	2.2	4.5	6.7
5	1.9	4.5	6.4
Average	2.04	4.64	**6.68**

From table above, average time taken to complete the task is 6.68s. The result is then compared with engineering target set at specifications phase. Initial engineering target for time taken was 10s, thus the prototype action time is 3.32s faster than target. Furthermore, the gripper is able to grip both type of workpieces which is cube and cylinder shape.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

After the prototype testing conducted, final results had been obtained and conclusion can be made with regards to the objectives. Table 17 below shows the final results for this project:

Table 17: Final results

No.	Specifications	Results
1	Dimensions not exceed 1m length X 1m width X 1m height	0.69m length X 0.57m width X 0.72m height
2	Total weight not exceed 10kg	Total weight of 8.2kg
3	2 workpieces shape, cube and cylinder	Able to grip and lift both shapes
4	Minimum gripping force of 27.5N	40N gripping force
5	Maximum gripping range of 800mm	Gripping range of 460mm
6	Maximum action times of 10s	Average action time taken is 6.68s
7	Avoidance of damage to workpieces	No damage to workpieces
11	Voltage for power supply not exceeding 24V	Uses 12V of power supply

It is shown that the prototype constructed had been able to be built within specifications required.

With respect to primary project objectives, the outcome of project is that a prototype of a robot gripper mechanism had been constructed. Along the project progress, a new design together with its analysis had been performed. Dynamic simulation analysis had been performed to fulfill secondary objective that is to verify analysis using simulation software on dynamic mechanism.

5.2 Recommendations

After the completion of the prototype, the project is concluded. However there are several issues during the project progress and on the results. Thus, recommendations can be made such as:

i. During the development of engineering specifications and development of concepts, most of the phases require brainstorming as well as references from journal and handbooks to obtain as many ideas possible. In this case, more time given for this phase would result in more ideas and could lead to better understanding its specifications.

ii. Development of customer's requirements is preferably to be without specific parameter values. This is to avoid narrowing down to specific concepts to early while discarding potentially good concepts.

iii. Action time taken during prototype testing is slower than evaluated time taken. This may caused by load of workpiece that slows the speed of motor. However, this can be further researched.

iv. Proximity switch used as sensor are not reliable, that causes several unsuccessful testing. Further study can be performed on sensor selection and evaluation.

v. Development of customer requirement can be constructed by using Quality Function Deployment (QFD) method to gain better outcome.

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APPENDICES

i. Gantt chart (Project schedule)
ii. Robot gripper technical drawings
iii. Robot gripper assembly drawings
iv. Schematic representation of tolerances for object provision and gripping point
v. Imperfections in gripper finger
vi. Examples of optimum prehension settings
vii. Forces action on jaw grippers
viii. Rough classifications of possible gripper types

i. Gantt chart (Project schedule)

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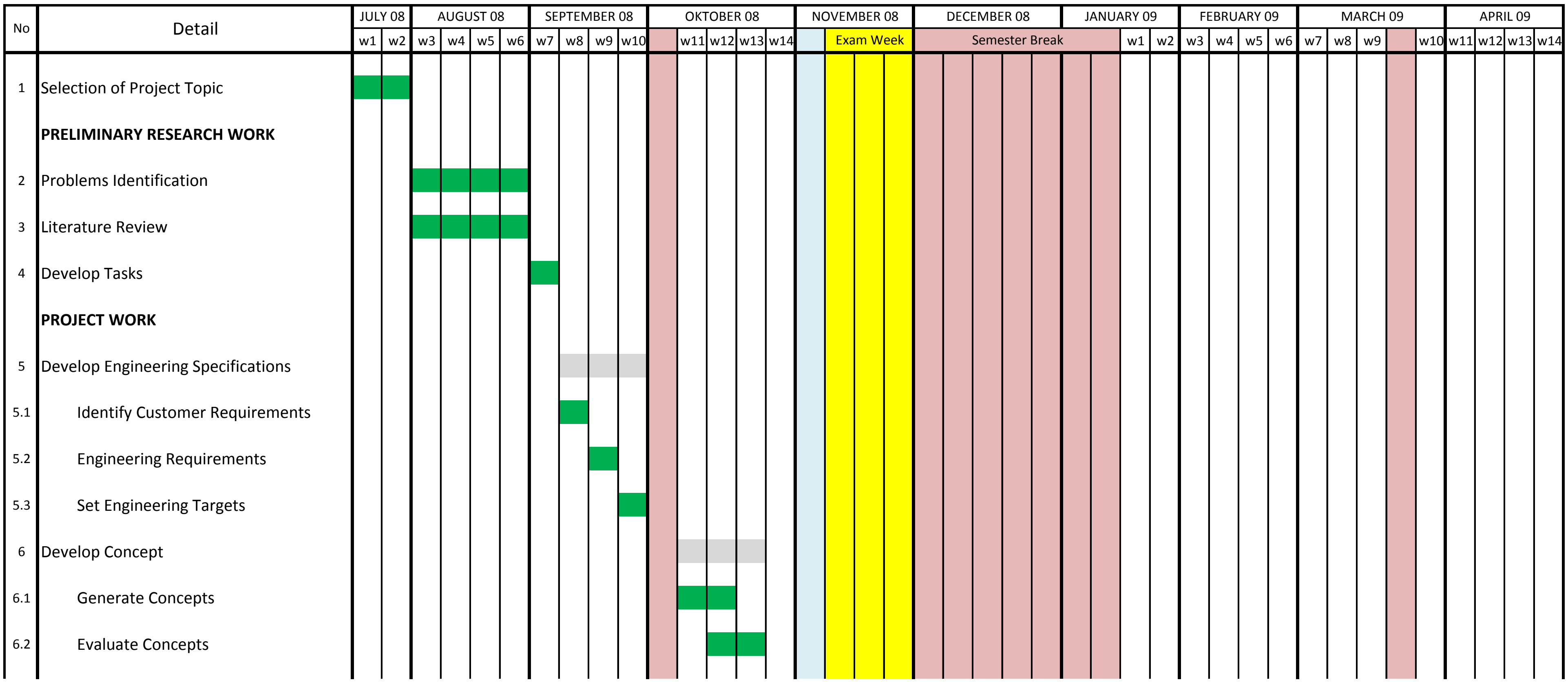
8566

Supervisor: Ms. Rosmawati Mat Zain

Final Year Project Schedule: Design of Robot Gripper for Robocon Robot Competition

MASTER SCHEDULE (2nd Draft)



i. (cont'd) Gantt chart (Project schedule)

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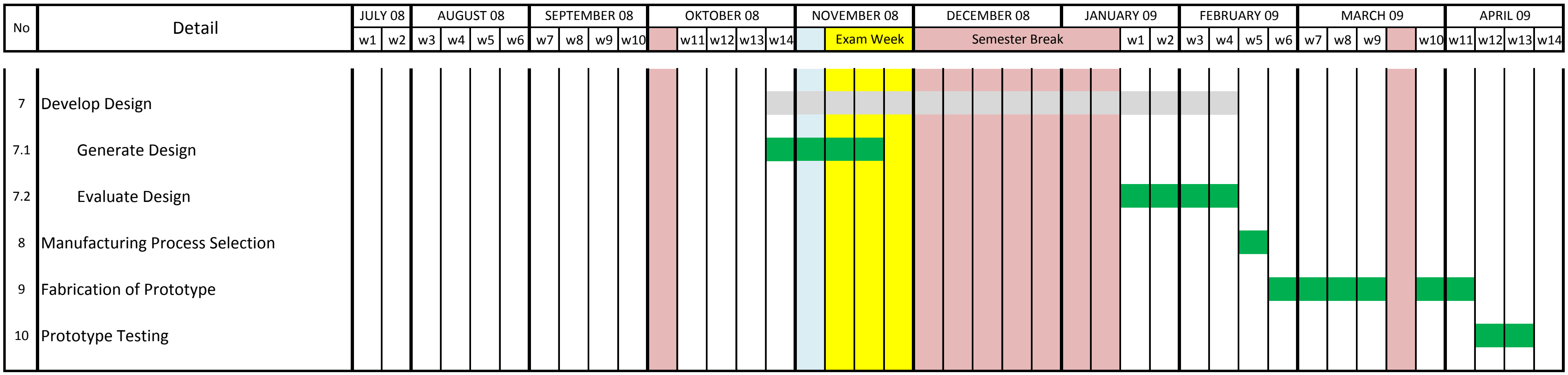

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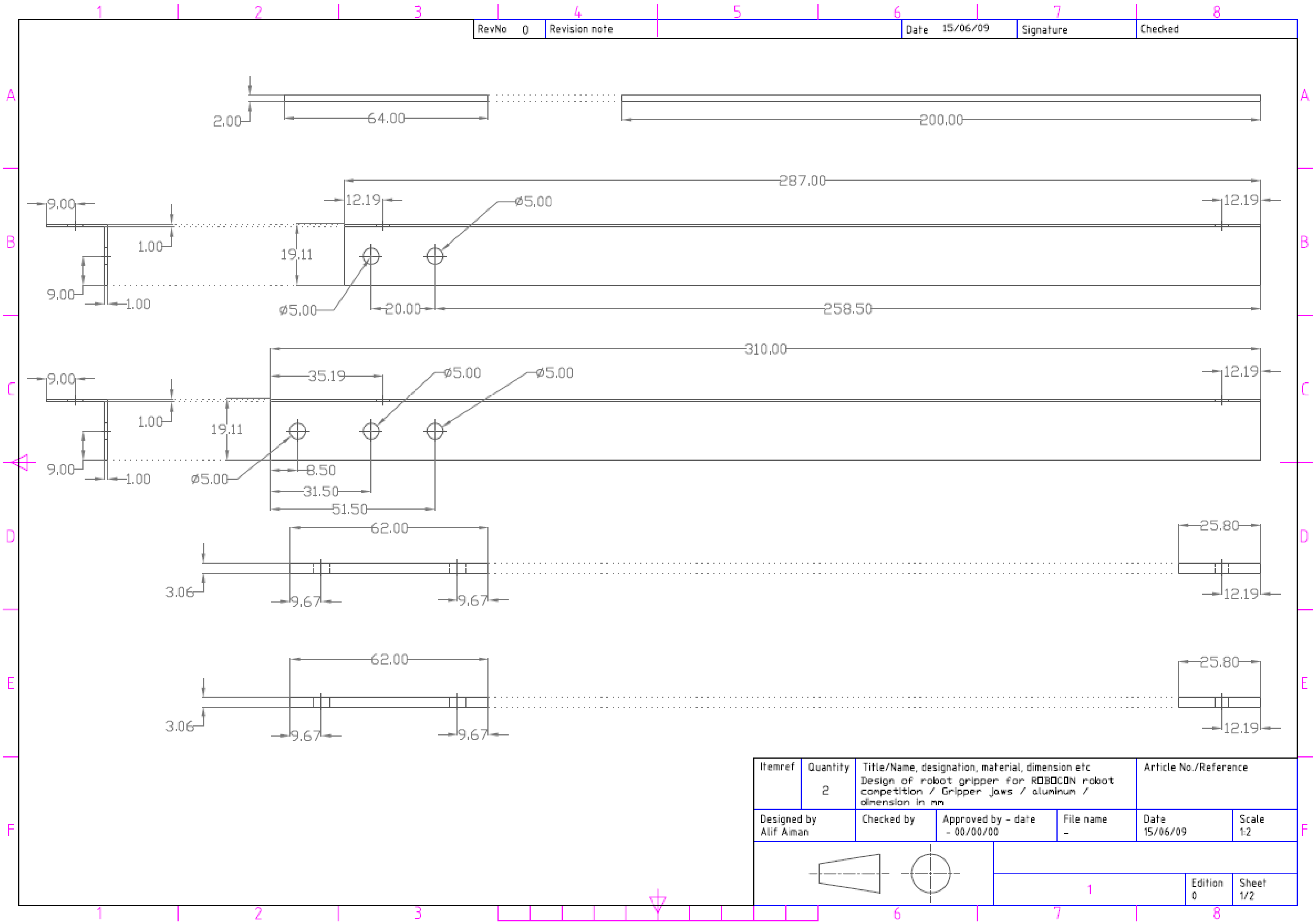

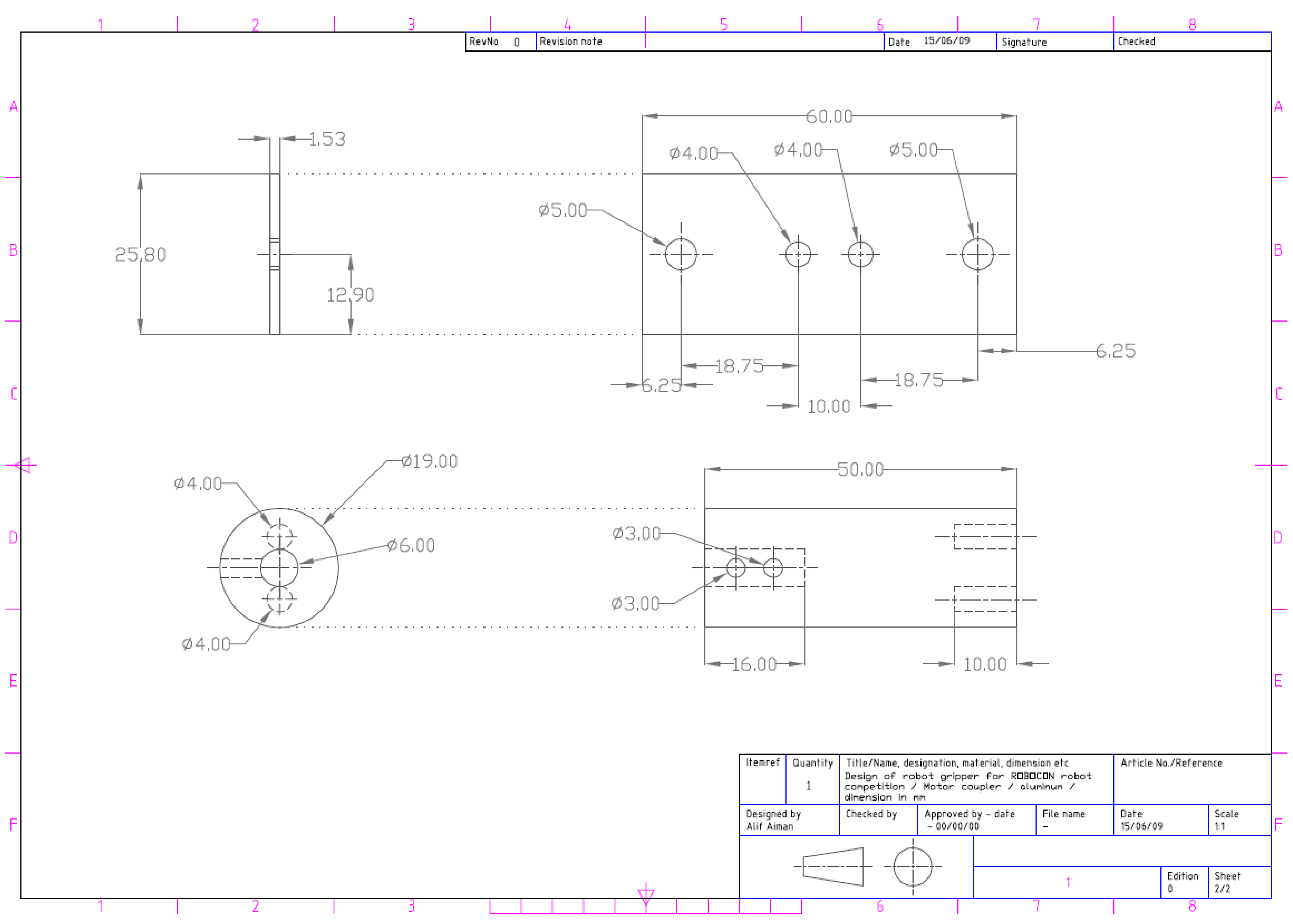

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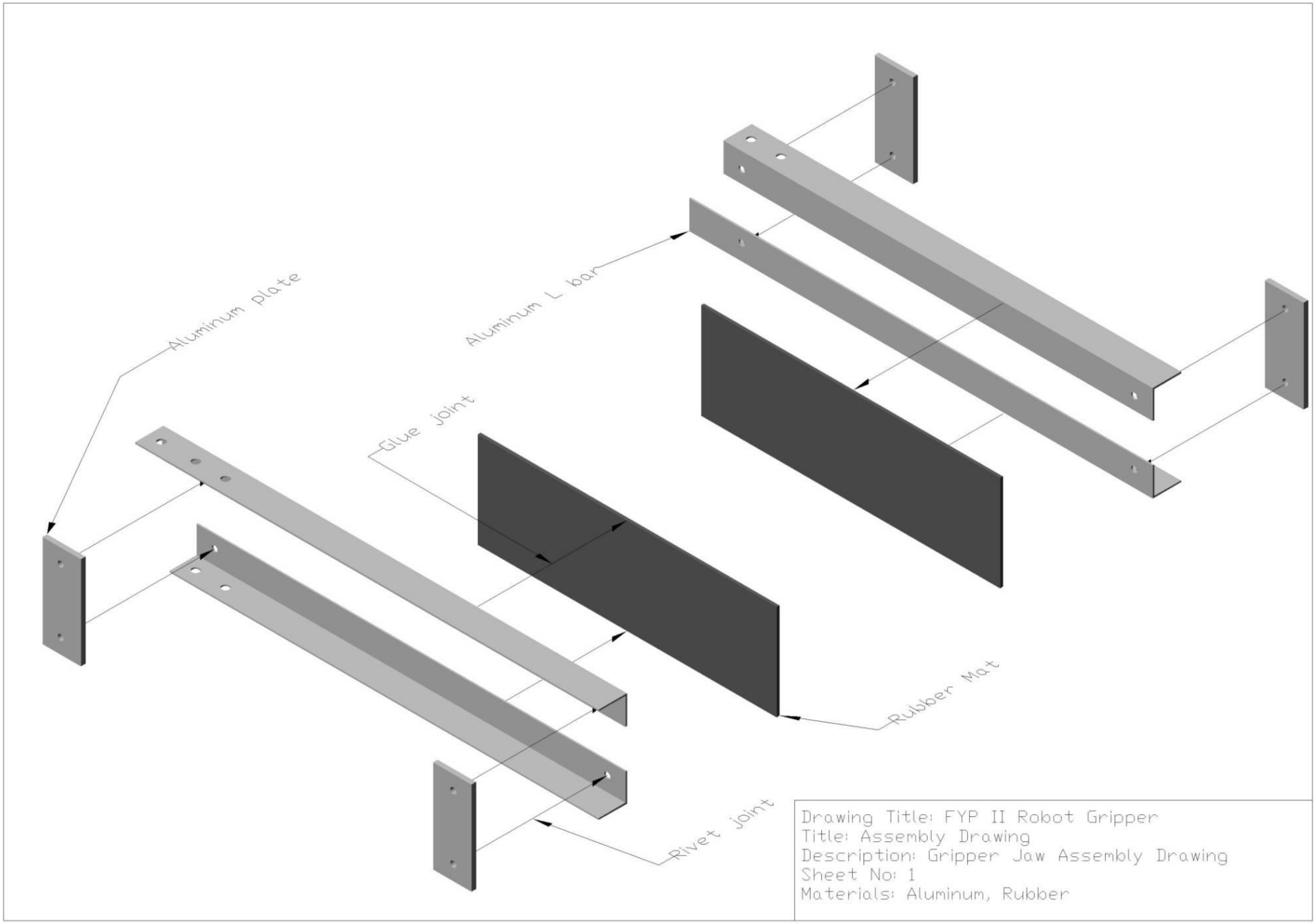
iii. Robot gripper assembly drawings



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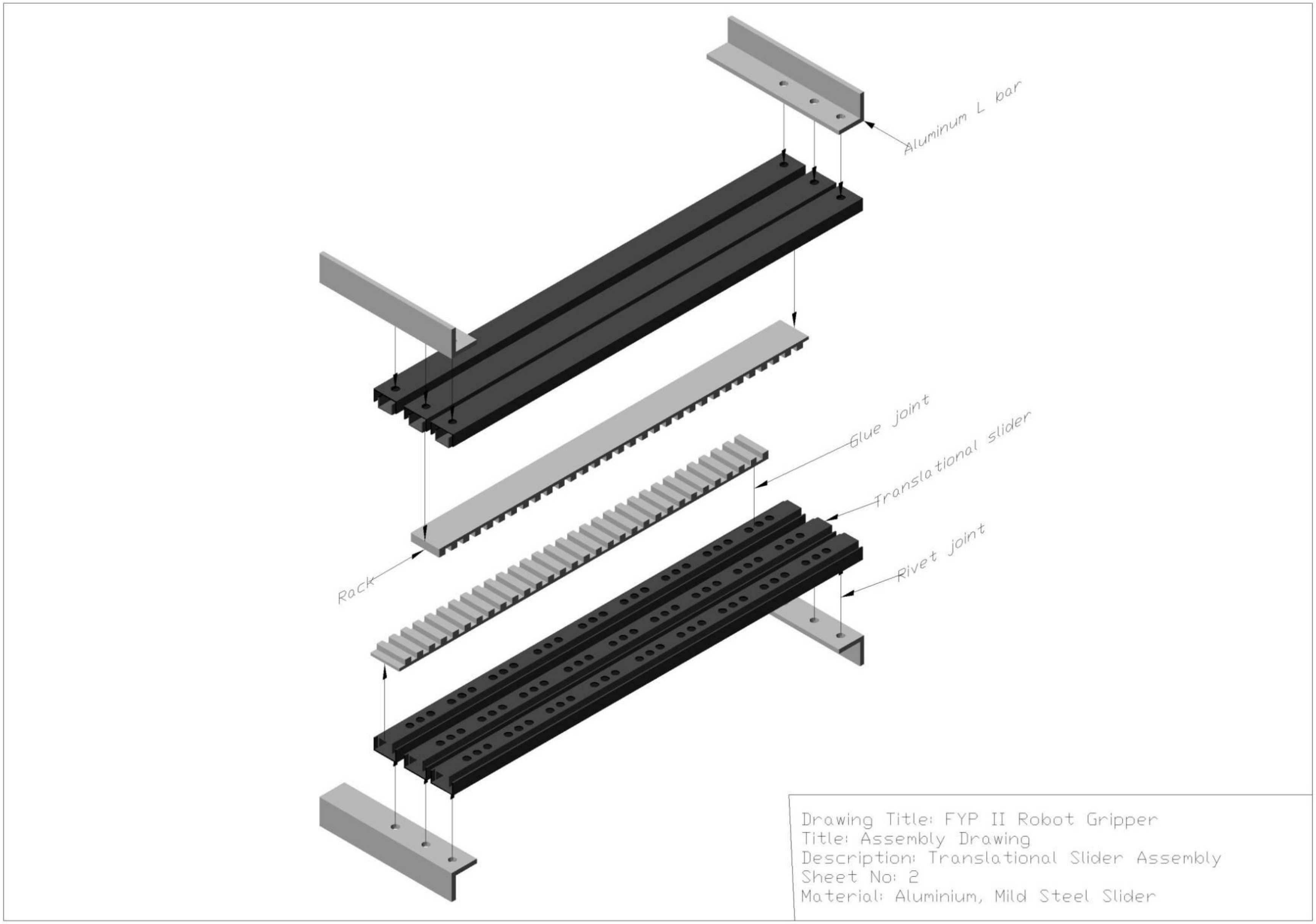

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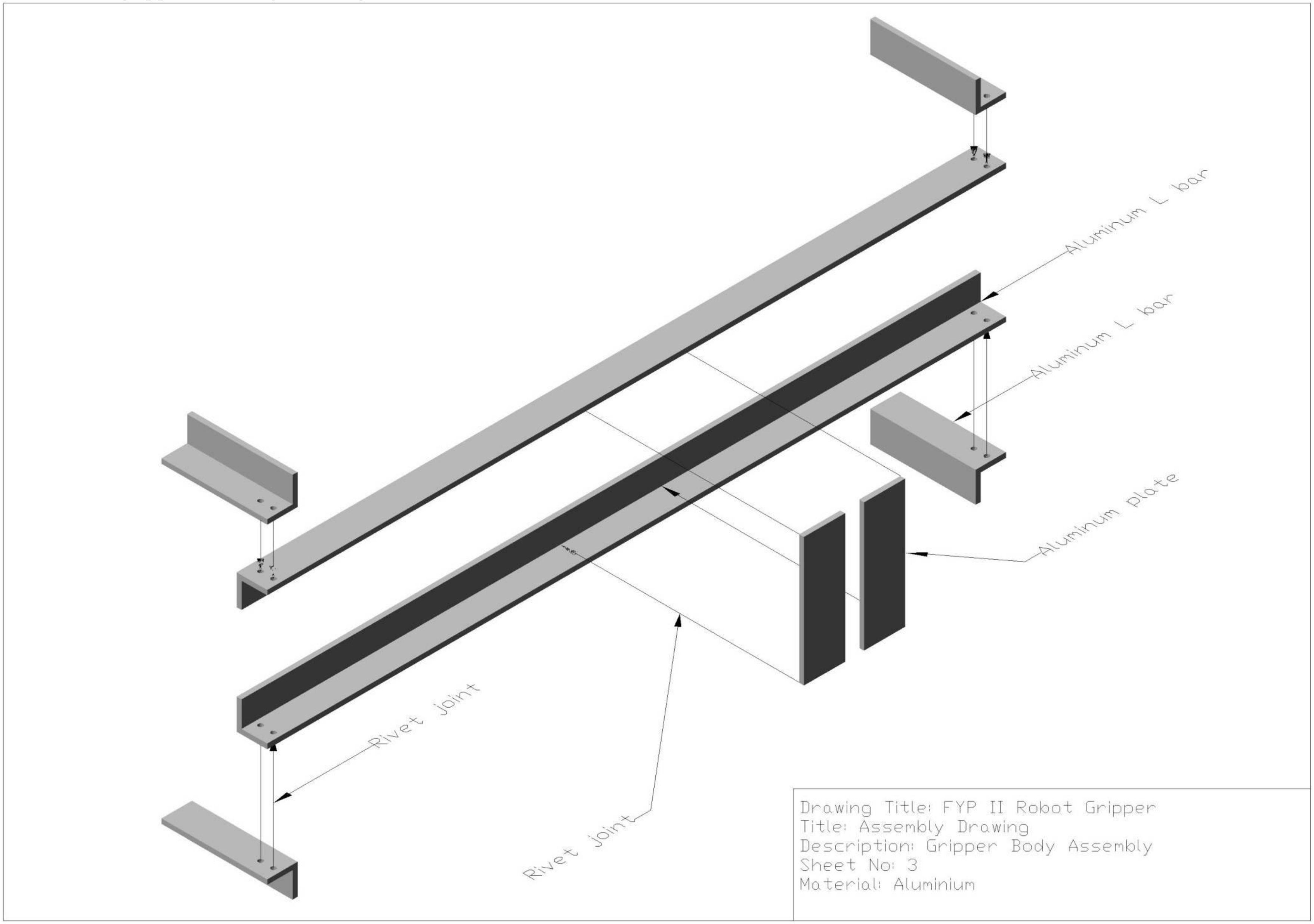

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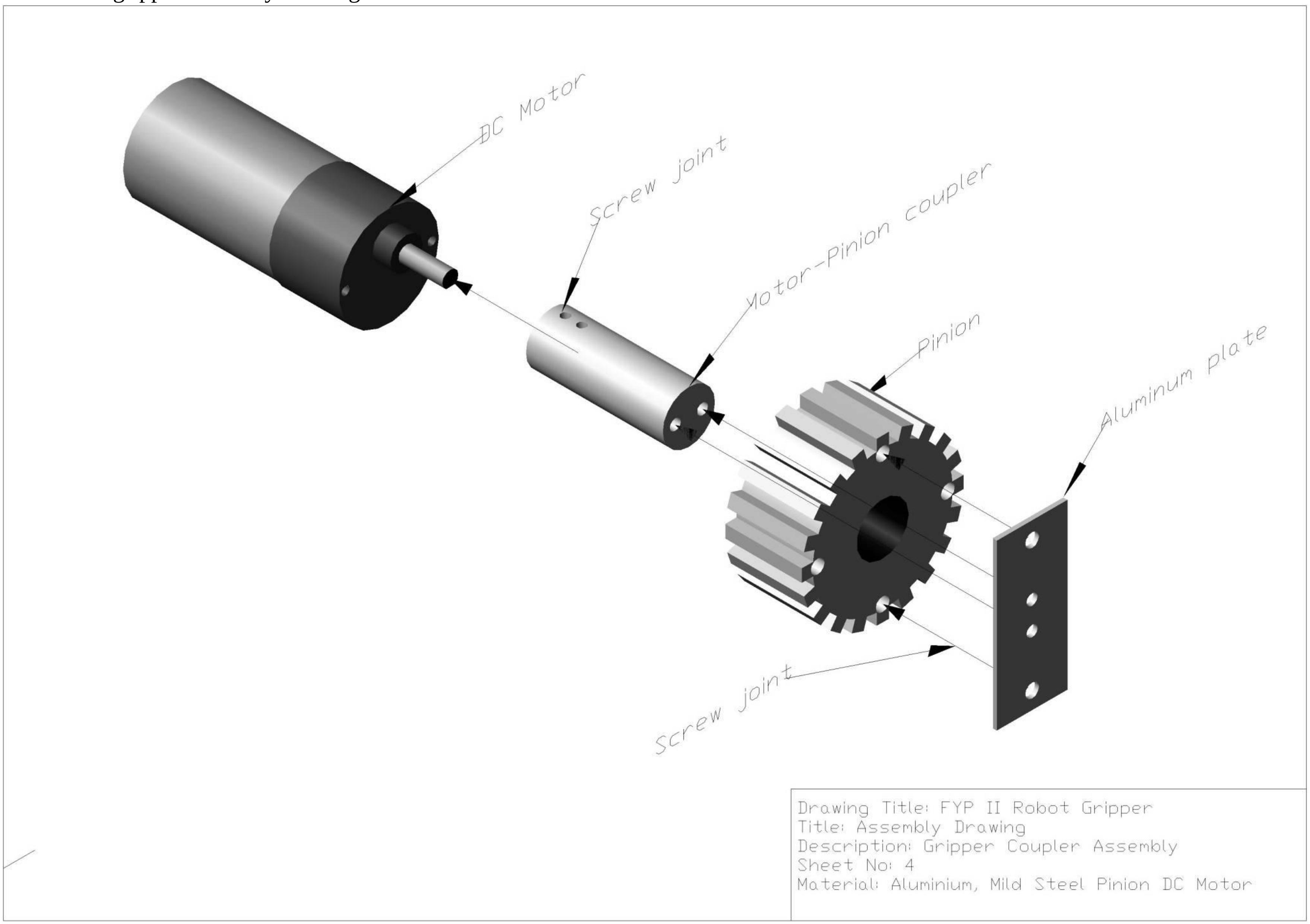
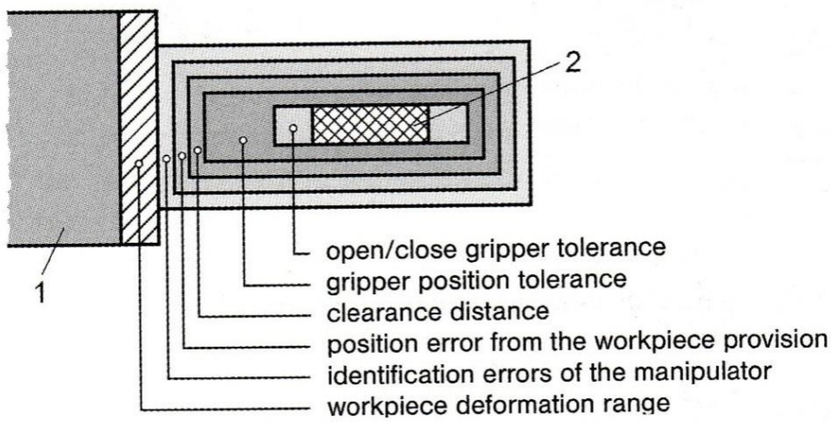


iii. Schematic representation of tolerances for object provision and gripping point



iv. Imperfections in gripper finger

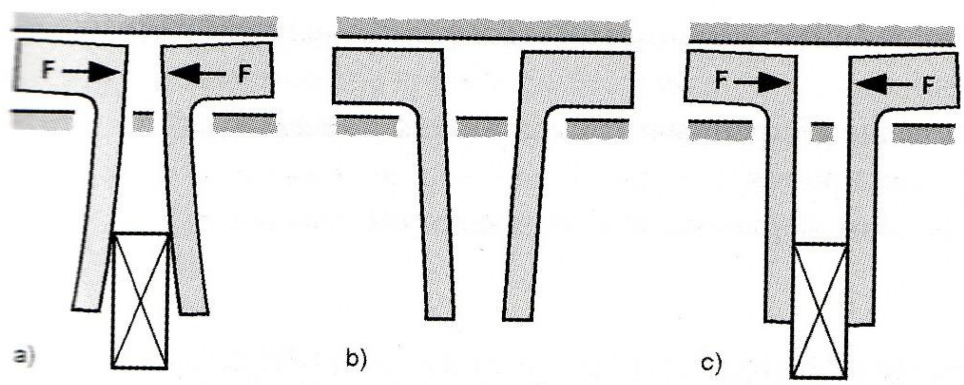
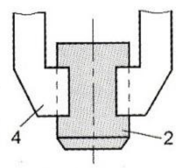
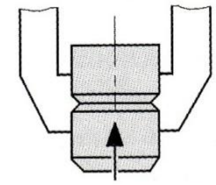
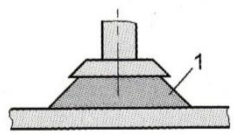
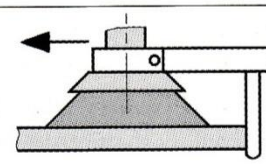
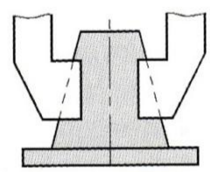
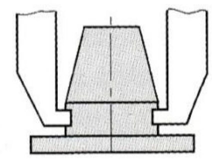
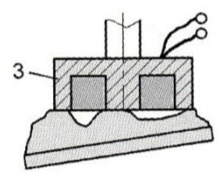
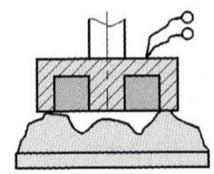
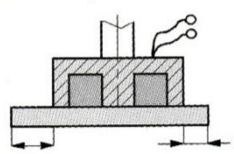
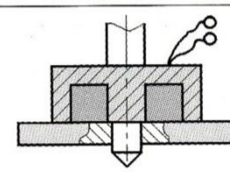
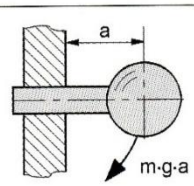
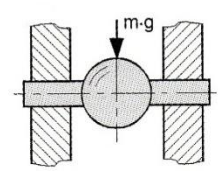


Fig. 2.36: Loss of parallelism with long fingers and large gripping forces [2-15]
a) gripping position for precisely right-angled fingers, b) preshaped fingers in unloaded state, c) gripping procedure for a gripper with preshaped fingers, F gripping force

v. Examples of optimum prehension settings

explanation	unfavourable	better
Shape matching allows for better transmission, e. g. of impactive forces, than pure force matching.		
Oiled steel sheets can slip from a rapidly moving transverse suction head if a constraint is not provided.		
Parallel prehension areas are always better and where possible should be deliberately formed on the workpiece.		
Astrictive prehension of, for example castings, requires a high degree of surface contact.		
Centring elements, e. g. bolt and holes, can be added to ensure improved prehension with astrictive methods.		
The centre of gravity of the component should lie between the gripper jaws so that there are no tilting moments M leading to displacement ($M = m \cdot g \cdot a$).		

vi. Forces action on jaw grippers

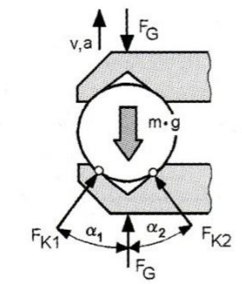
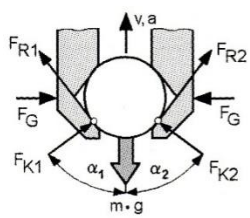
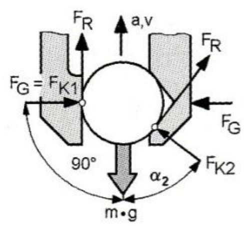
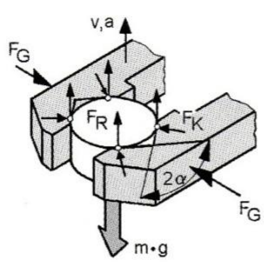
	sketch	contact forces	gripping force, upwards
shape force-mating		$F_{K1} = \dfrac{m(g+a)\sin\alpha_2}{\sin(\alpha_1+\alpha_2)}$ $F_{K2} = \dfrac{m(g+a)\sin\alpha_1}{\sin(\alpha_1+\alpha_2)}$	$F_G = m(g+a) \cdot S$
shape and friction mating		$F_{K1} = \dfrac{m(g+a)}{2 \cdot \cos\alpha_1}$ $F_{K2} = \dfrac{m(g+a)\tan\alpha_2}{2 \cdot \cos\alpha_2}$	$F_G = \dfrac{m(g+a)}{2} \tan\alpha \cdot S$
		$F_G = m(g+a)\tan\alpha_2$ $F_{K2} = \dfrac{m(g+a)}{2 \cdot \cos\alpha_2}$	$F_G = F_{K1} \cdot S$
pure friction mating		$F_K = \dfrac{m(g+a)}{4 \cdot \mu}$	$F_G = \dfrac{m(g+a)}{2 \cdot \mu} \sin\alpha \cdot S$

Fig. 2.45: Forces acting in a parallel jaw gripper with double-sided or single-sided prismatic jaws for a linear motion [2-20]
a linear acceleration (recommended values: electrical shaft 6 m/s^2, electrical tooth belt 20 m/s^2, servopneumatic 25 m/s^2, pneumatic 30 m/s^2, pneumatic rotation or pivoting gears 40 m/s^2), *g* acceleration due to gravity, *m* mass, *S* safety factor, *v* velocity, μ friction coefficient

vii. Rough classifications of possible gripper types

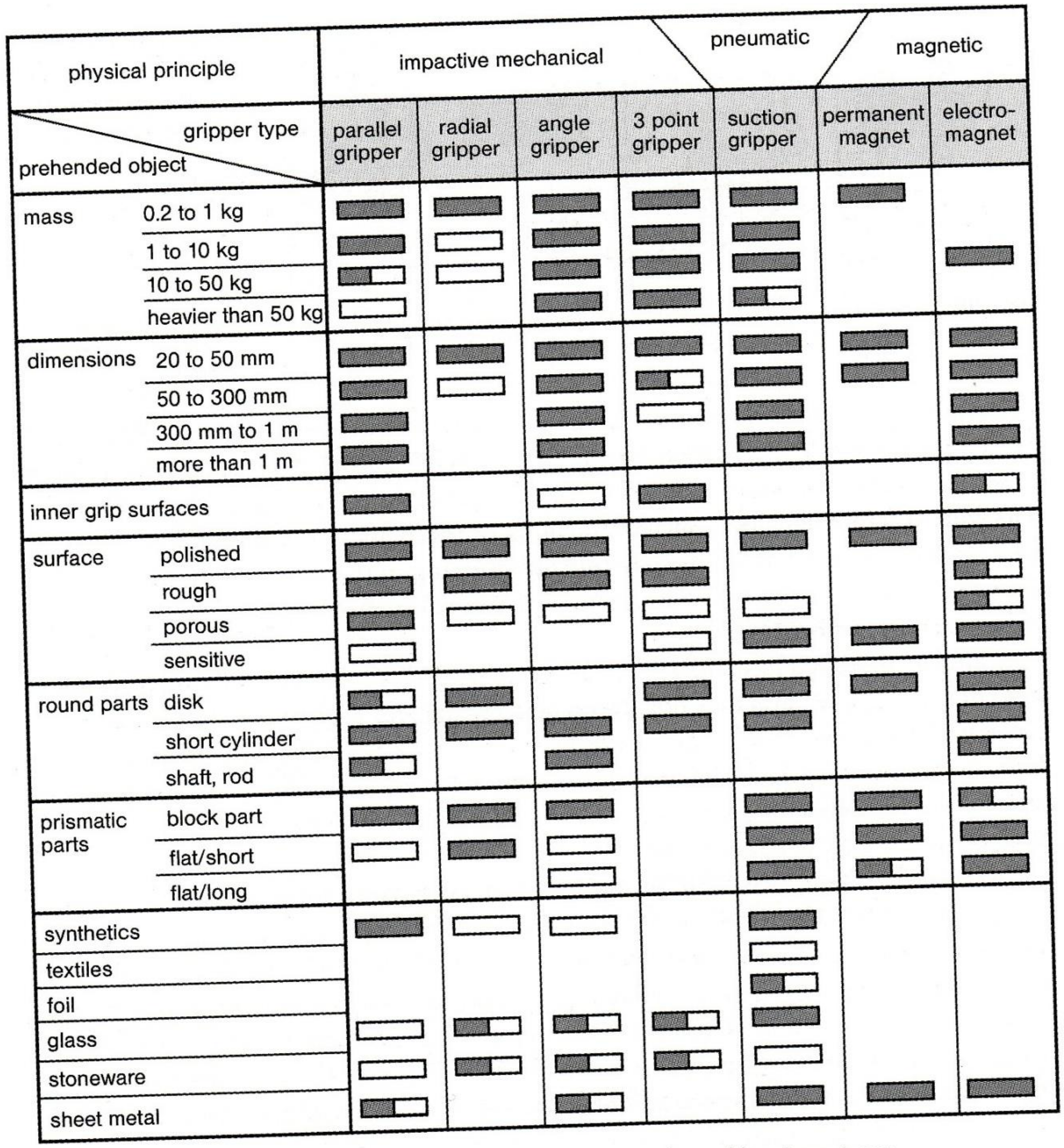


Fig. 2.60: Rough classification of objects and the assignment of possible gripper types. filled stripe = suitable; empty stripe = conditionally suitable